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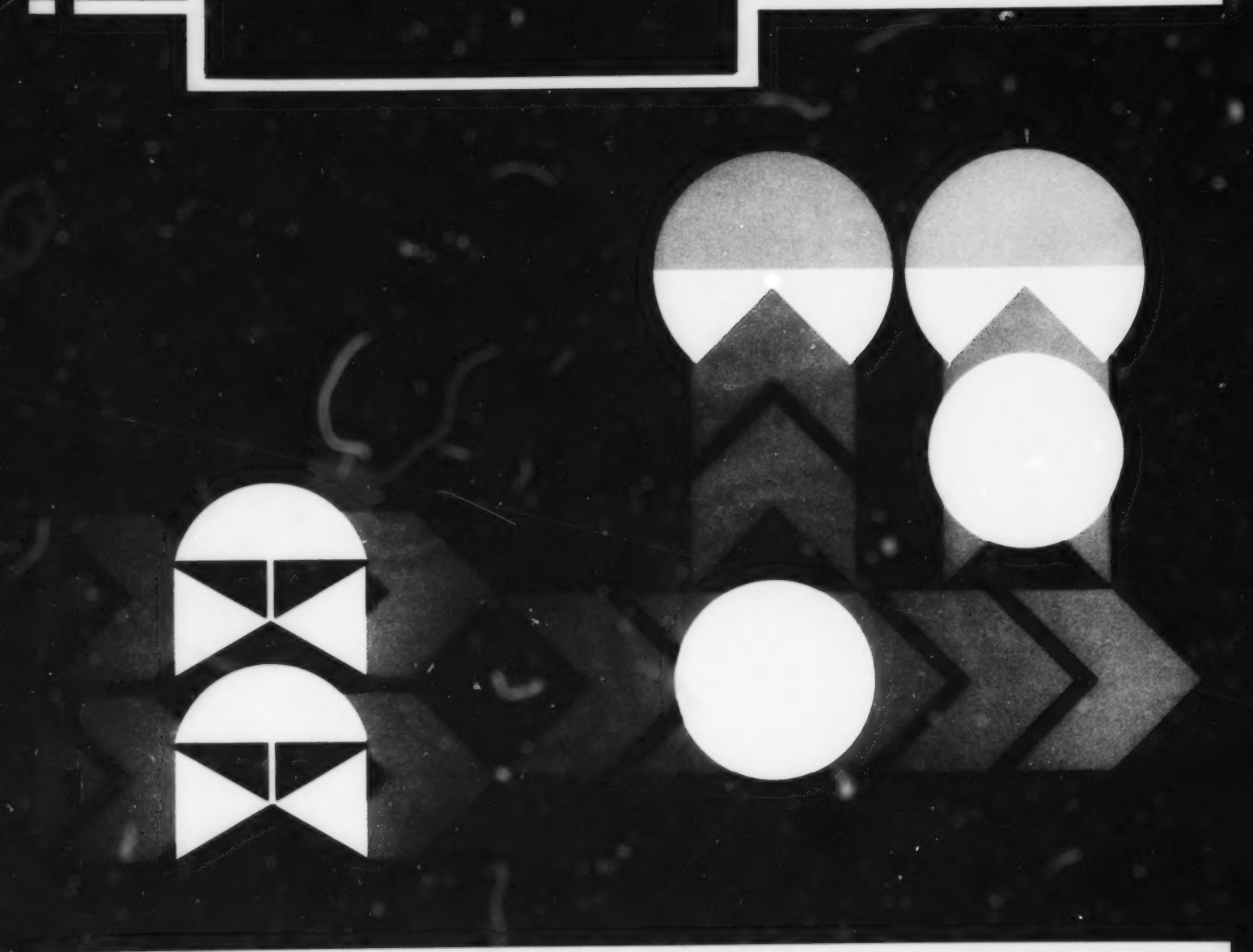

THE UNIVERSITY OF CALGARY

A Study of Vapour-Assisted Gravity Drainage of Heavy Crudes and Bitumen Using Propane: Further Development of the Vapex Process

FINAL REPORT - Phase 2

by:
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EXECUTIVE SUMMARY

The report describes a laboratory study aimed at the development of a new, low heat requirement recovery method for heavy oils and bitumen. The method, termed Vapex, employs saturated propane (or generally hydrocarbon) vapours to extract heavy oils from the formation. It utilizes pairs of horizontal wells and is closely related to the Steam-Assisted Gravity Drainage process but with the steam chamber replaced with a chamber containing hydrocarbon vapour at its dew point. The use of horizontal wells should make the rate of production economic.

The laboratory research utilized a scaled, physical model with 62 thermocouples confined in a pressure vessel, 2 load cells and a computer interface for recording and displaying data. It was found that, by choosing the appropriate conditions, the quality of the produced heavy oil or bitumen can be substantially improved as a result of an in situ deasphalting. The new oil is lighter, requires less diluent for transport in a pipeline, and is more suitable for direct refining without the costly intermediate upgrading step. The asphaltenes remain in the reservoir where they were deposited.

Injection of propane alone at reservoir temperature results in a process with negligible heat losses which is suitable for thin or low porosity reservoirs. Combining propane with steam results in a hybrid process characterized by a steam chamber confined to the area of the injector/producer and a separate vapour chamber spread laterally over a wide expanse of the reservoir. The heat near to the producer strips the propane and recycles it back into the vapour chamber which is kept at temperatures only slightly above that of the reservoir. The heat also prevents flow impairment through asphaltene deposition in the area of the producer.

Vapex is a promising new approach which, with further development, should offer potential economic advantages in many of Canada's reservoirs. In addition, the resulting oil can be lighter and of a better quality.

SOMMAIRE

Ce rapport est destiné à décrire une étude de laboratoire visant le développement d'une méthode nouvelle à très basse exigence de chaleur pour la récupération des pétrole lourds et des bitumes. La méthode, dénommée Vapex, utilise des vapeurs de propane saturées (ou généralement des hydrocarbures) pour extraire les pétroles lourds des gisements. La méthode utilise des paires de puits horizontaux analogue au procédé de drainage par gravité assisté par la vapeur mais avec la chambre de vapeur remplacée par une chambre contenant des vapeurs d'hydrocarbures à leur point de rosée. L'utilisation des puits horizontaux contribuera à un taux de production très économique.

L'étude de laboratoire utilise un modèle à l'échelle avec 62 thermocouples dans un récipient sous pression, 2 cellules de charge et un ordinateur pour enregistrer et indiquer les données. Un choix judicieux des conditions opératoires, permettant un désasphaltage in situ, peut améliorer considérablement la qualité des pétroles lourds ou des bitumes. Le pétrole produit est plus léger, exige moins de diluant pour le transport dans le pipeline et convient parfaitement au raffinage directe sans étapes coûteuses de valorisation intermédiaire. Les asphaltènes resteront dans le réservoir où ils sont déposés.

L'injection de propane seul à la température du réservoir permet d'obtenir résultat d'un procédé avec des pertes de chaleur négligeable qui convient à des réservoirs avec une porosité mince ou basse. La combinaison de propane et de vapeur détermine un procédé hybride caractérisé par une chambre de vapeur limitée à la région de l'injecteur/producteur et une chambre séparée de vapeur étalée latéralement sur une large région du réservoir. La chaleur à côté du producteur retire et recycle le propane dans la chambre à vapeur qui est maintenue à des températures légèrement supérieures à celle du réservoir. La chaleur aussi empêche la détérioration de l'écoulement à travers les dépots d'asphaltènes dans la région du producteur.

Vapex est une approche nouvelle et prometteuse, et avec de nouveau développement, doit offrir des avantages économiques potentiels pour plusieurs réservoirs au Canada. En plus, le pétrole produit peut être plus léger et de meilleur qualité.

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1. ABSTRACT

This final report summarizes the Phase 2 development of a proposed new recovery method for an in situ production of heavy oils and bitumen that was carried out under a contract with Energy, Mines and Resources Canada between October 1989 and October 1991. The new approach makes use of the injection of saturated hydrocarbon vapours alone at reservoir, or slightly above the reservoir temperature, or the injection of the vapours in conjunction with steam. The attractive features of the method are twofold: lower heat losses into the under- and overburden in thin Lloydminster-type reservoirs (as compared with conventional steam injection, which is effective but tends to be uneconomic in thinner and/or lower porosity reservoirs), and the production of a new, better quality, in situ upgraded oil. This new oil is more suitable for direct refining without the costly intermediate upgrading step.

The method, termed 'VAPEX', utilizes two horizontal wells and is closely related to the Steam-assisted Gravity Drainage (SAGD) process [1] in which the steam chamber has been replaced with a chamber containing hydrocarbon vapour near its dew point. The extension and application of the SAGD concept and ideas to VAPEX offers many new and exciting possibilities.

Phase 1 development, that ended in October 1989, was a feasibility study in a small (7 x 7 cm) Hele-Shaw, and later, packed cell. Phase 2, which is documented in this report, describes experiments in a larger two-dimensional scaled model. Phase 3 is ongoing and was initiated in November 1991 with EMR and industrial support. It includes further experimental work and it will also explore the possibility for a commercial, field scale development in the form of one or more field demonstration pilots.

The Phase 2 study initially investigates propane injection into a cell filled with Lloydminster heavy oil at the end of a hot waterflood. Later experiments examine the injection of propane only and its effect on asphaltene precipitation and oil viscosity. Some exploratory runs were carried out in which saturated ethane vapour was used as a solvent. In the final experiments, propane vapour was injected concurrently with steam into the cell filled with Cold Lake bitumen. A separate set of experiments was also

performed to study the mixing of Cold Lake bitumen with propane in a cylinder filled with glass beads acting as a substrate for deposition of asphaltenes. The viscosity of the resulting oil was determined as a function of gas-to-oil ratio in the apparatus. The Phase 2 study ended with a theoretical investigation of the adiabatic mixing of propane with a cold reservoir oil and the effect of heat of solution of propane vapour on the temperature rise of the reservoir.

2. INTRODUCTION

In Phase 1 of the development of the Vapex process [2,3], we have shown that a propane vapour injected near its dew point into a scaled model of a reservoir, can be an attractive way of recovering a Lloydminster type heavy oil. The rate of drainage from a 1500 ft horizontal well drilled at the bottom of a 10 m pay zone with a permeability of 1 darcy would produce, according to the scaling parameters, about 155 bbl/day of heavy oil. The work was carried out in a small, two-dimensional Hele-Shaw, and later, in a packed cell. The rate of production was found to be a function of temperature and was high at modest temperatures (eg. 0.1 bbl/ft/d in the range of 40 to 50°C). Rather than injecting large amounts of propane and relying entirely on its latent heat of solution (or condensation), the cell was raised to this temperature range by injecting hot water together with a small amount of propane vapour. A vapour chamber (or solvent chamber) which replaced the original oil was formed and the drainage of diluted warm oil occurred in a thin layer adjacent to the vapour/oil interface.

The recovery mechanism involves the diffusion and condensation of propane vapour into the oil surface with subsequent warming and swelling of the interface. The combined effect of the heating of oil due to the release of the latent heat of condensation of propane, the dilution of the oil with liquid propane and the precipitation and deposition of asphaltenes on the solid matrix results in lowering the oil viscosity to the point where drainage flow occurs in the boundary layer adjacent to the interface. This flow exposes a fresh surface of oil and the process of dilution/heating/deasphalting and gravity drainage is repeated in a step-wise fashion. The extent to which these physical processes take place are, however, sensitive to the experimental conditions, and a further investigation is being undertaken in Phase 3 of the project to understand these fully.

The diluted oil is warmed by contacting hot water near the producer, is stripped of propane and drains out of the cell. The hot propane rises, warms up further on contact with hotter water near the injector and then condenses along the cold oil interface at the periphery of the solvent chamber. In the process, the propane carries its sensible and latent heat with it to the far reaches of the vapour chamber, making it

spread laterally. Most of the propane is therefore re-circulated within the solvent chamber where it transports heat from the hot water to the cold periphery of the chamber.

However, for each volume of oil recovered, a slightly larger volume of saturated propane vapour must be injected into the reservoir to maintain the reservoir pressure and to keep the propane vapour close to its dew point. Fortunately, one barrel of liquid propane produces about 27 barrels of saturated vapour at 20°C and the propane requirement could be diminished further by injecting steam or by working at lower temperatures. For instance, at 14°C, as many as 33 volumes of oil can be replaced with one volume of liquid propane in the form of its saturated vapour.

One shortcoming of the initial work (i.e., Phase I) was the small size of the packed cell (7 x 7 x 2.54 cm) which could not provide much data on the lateral spread of the solvent chamber. This information is important for estimating the extent of recovery far away from the producer, and therefore, the optimum horizontal well spacing in an upcoming pilot plant project. Scaling such a small cell to reservoir conditions may also be inaccurate, due to various end effects and many important mechanisms or phenomena, such as asphaltene precipitation and its effect on the impairment of drainage flow, may be overlooked.

In the development of Phase 2, which is the subject of this report, a much larger, two-dimensional physical reservoir model was employed. The investigation focused on the effect of asphaltene separation and deposition on the viscosity of the produced oil and on the drainage flow impairment. The producer was located in the bottom left corner of the cell and the spread of the vapour chamber was monitored by means of thermocouples, scanned by a computer, which were located at strategically important points in the cell.

The experimental investigation involved a propane/hot water injection, propane/steam injection and propane injection only. The oil production rates, percent recovery, G/O and W/O ratios were then evaluated and compared. The propane injection without steam or hot water was designed to test the feasibility of such a process in some reservoirs.

A separate study of Cold Lake bitumen-propane interaction, or mixing, was undertaken to assess the extent to which oil viscosity is reduced by asphaltene precipitation on the substrate as a result of contact between oil and varying amounts of propane at a constant temperature. The results have established a set of guildelines for in situ deasphalting and will be utilized to optimize the experimental conditions in further scaled model experiments. Encouraging results were obtained in this area. They opened the way for a Phase 3 study which will include more experimental laboratory work and the initiation of a pilot plant project to test the Vapex process in the field.

3. EXPERIMENTAL WORK

3.1 Phase 2 VAPEX Apparatus

The basic apparatus was designed for simultaneous propane-water injection into a large packed cell. Later on, parts of it were modified to facilitate propane-steam injection and propane injection by itself.

The apparatus was designed around a 1200 psi tubular pressure vessel (ID = 36.3 cm) that accommodated a 78 x 30 x 7 cm (outside dimensions without wheels and connectors), two-dimensional packed cell equipped with 62 thermocouples. The limitation on the number of thermocouples in the cell was imposed by the availability of terminals on the Taurus interface. The Taurus has a total of 64 terminals, two of which were reserved for the load cells.

The 62 thermocouples in the cell and the two load cells for weighing water and propane, respectively, were monitored by a Taurus/PC and the results recorded in a file or printed out. The overall view of the Vapex apparatus is shown in Fig. 3.1.1. This figure also shows the gas collectors, the water pre-heater tank on a load cell, the PID controllers, the steam line from the steam generator and the associated lines and connections.

A detail view of the piping and thermocouple connections through the vessel flange is seen from the photograph in Fig. 3.1.2, which also shows the steam knock-out pot. Since the flange acted as a huge heat sink, this small cylinder was required to separate condensed water from steam and to facilitate the injection of dry steam into the cell, (i.e., in those experiments where steam was used). A schematic of the whole apparatus is given in Figure 3.1.3. Details of the apparatus are discussed in the following subsections.

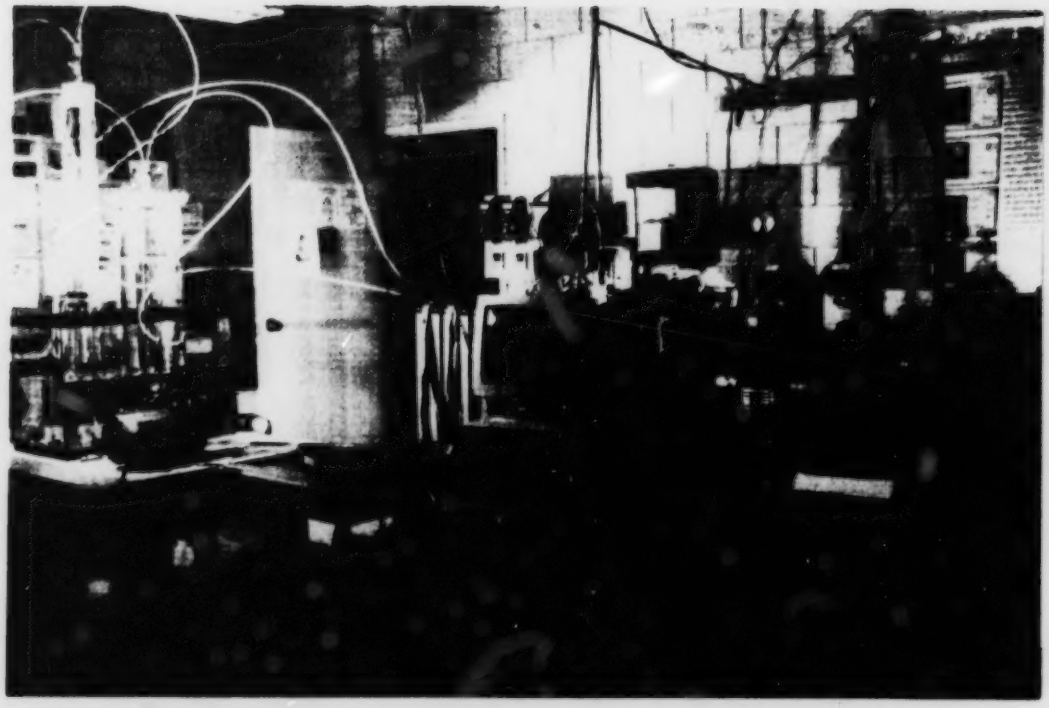


FIG. 3.1.1. OVERALL VIEW OF THE VAPEX APPARATUS

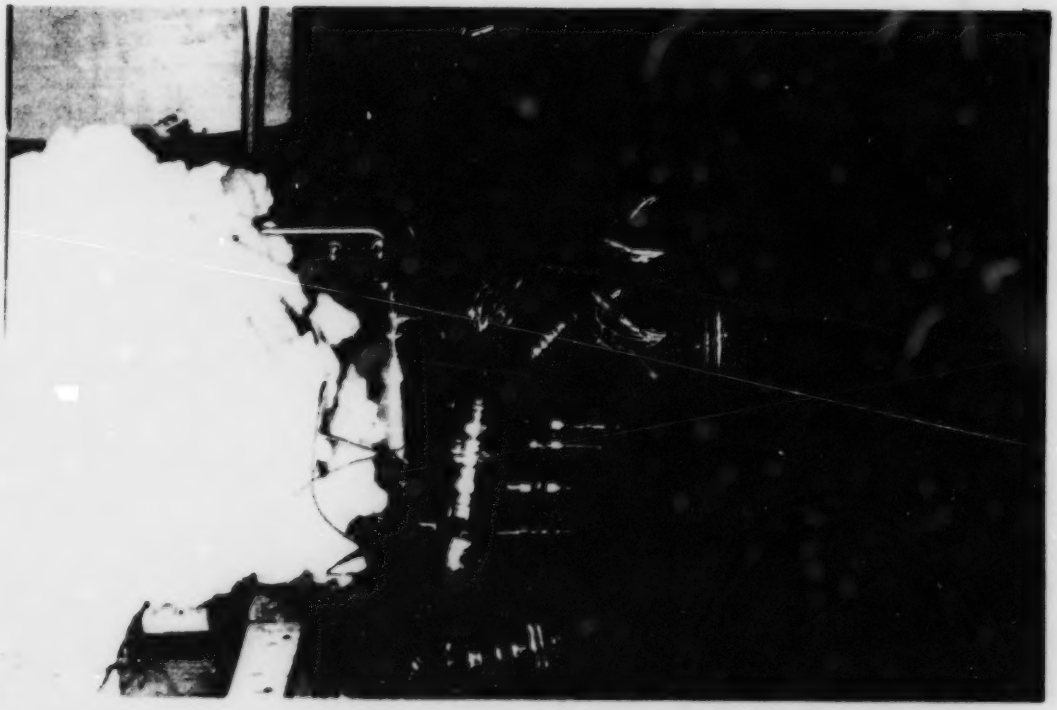


FIG. 3.1.2. DETAIL OF CONNECTIONS THROUGH THE FLANGE

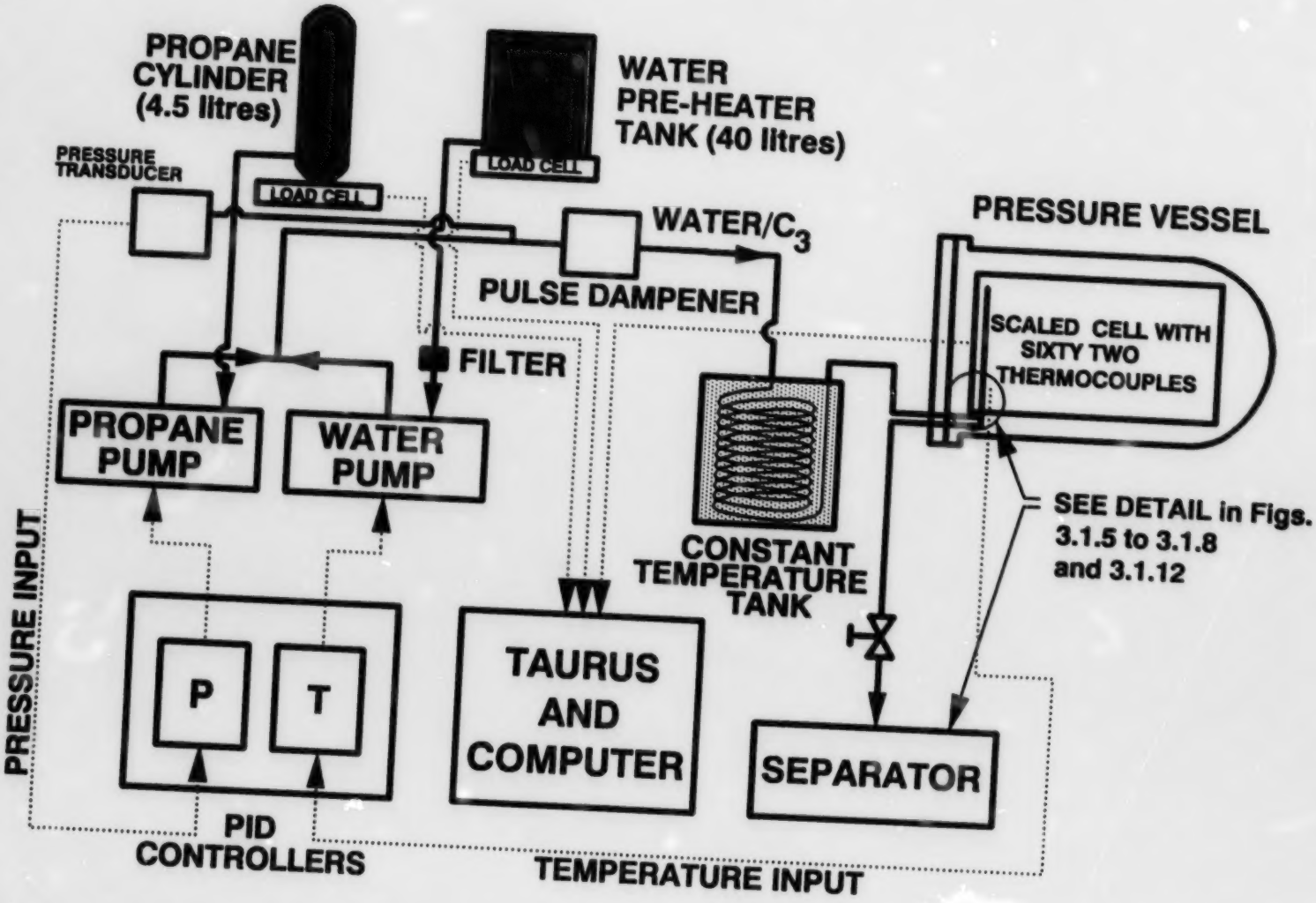


FIG.3.1.3. DIAGRAM OF THE SCALED-UP VAPEX APPARATUS

Cell:

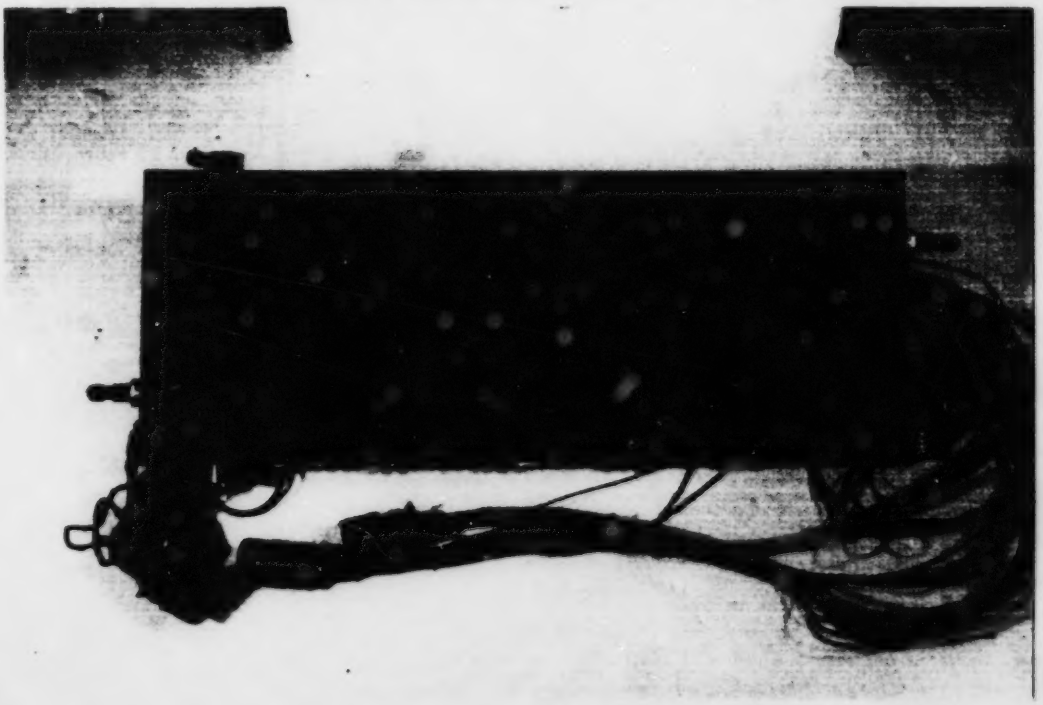
A diagram and a photograph of the cell are shown in Fig. 3.1.4. The two-dimensional, scaled model of the reservoir (the cell) was made out of fibre-reinforced phenolic resin to withstand high steam temperatures as well as to retain heat within the low thermal conductivity walls. The cell could be dismantled into 3 sections for cleaning, and the tightness was assured by O-rings running continuously along the edges of the middle section of the cell. During a run, the inside production pressure was counter-balanced by confining nitrogen pressure at 10-50 psi above the production pressure. The cell was equipped with 62 thermocouples connected to a PC via a Taurus interface. It was insulated with cotton wool.

The location of the thermocouples in the cell and the main cell dimensions are given in Figure 3.1.4. The location of each thermocouple with respect to the origin is listed in Table 3.1.1. Figure 3.1.4 is drawn to scale and the active tips of the thermocouples were located in the plane dissecting the depth of the cell in half. The thermocouples used were manufactured by Versatile Measuring Instruments of Toronto or Gordon of Chicago and supplied by Lee Instruments & Supply Co. in Calgary. These thermocouples are J-type, 1/16 OD 316 stainless steel sheath, are ungrounded, have 3 inch immersion length and the tip is sensitive to heat.

All propane-water (or steam) piping and thermocouple connecting wiring was built into the flange of the vessel and all final connections to the cell were made while the flange was lifted on a crane and ready to be bolted to the pressure vessel (Fig. 3.1.2).

INSIDE HEIGHT = 21.70 cm
INSIDE WIDTH = 69.80 cm
INSIDE DEPTH = 3.4 to 3.5 cm
CELL VOLUME≈ 5.150 *l*
OIL VOLUME≈1.8 to 2.0 *l*
THERMOCOUPLES PROTRUDE 17 mm INTO THE CELL

FIG.3.1.4. VAPEX CELL WITH 62 THERMOCOUPLES



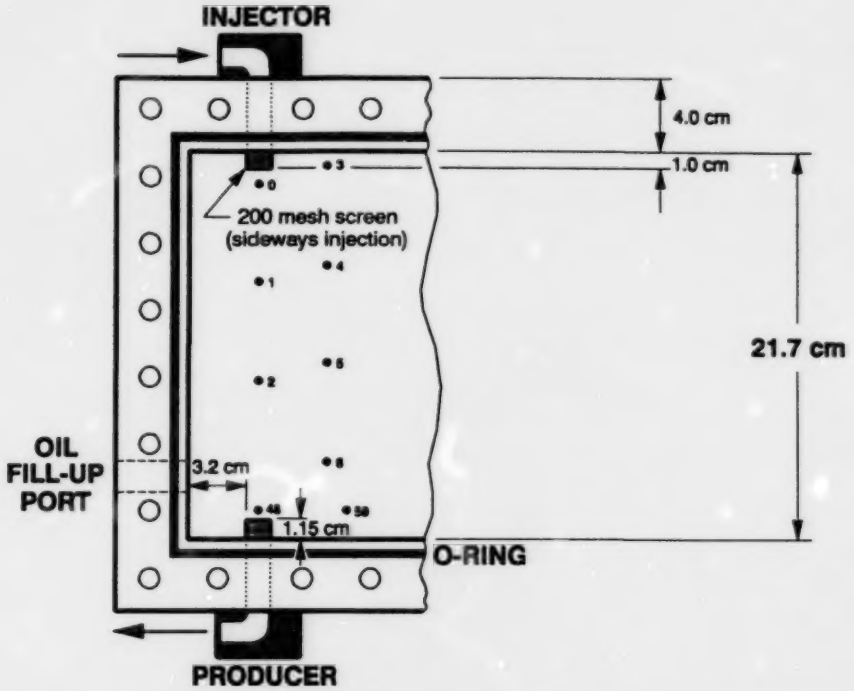


FIG.3.1.5. THE SEPARATE INJECTOR/PRODUCER

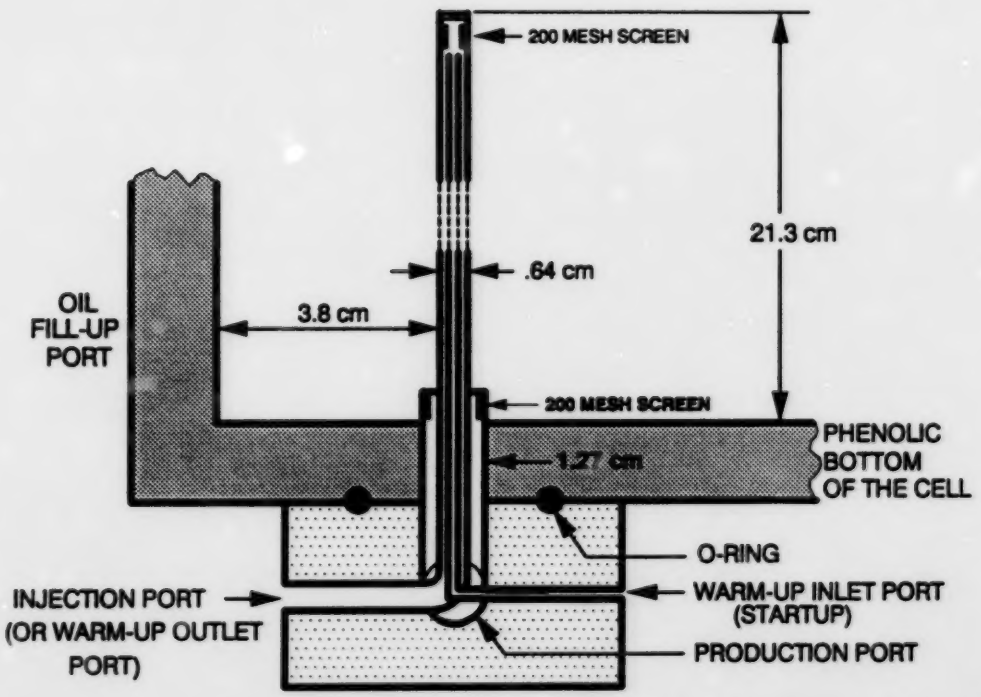


FIG.3.1.6. DETAIL OF VERTICAL INJECTION/PRODUCTION WELL

Table 3.1.1: Position of the 62 Thermocouples in the Vapex Cell
(origin is in the bottom left corner - see Fig. 3.1.4)

TC #	x(cm)	y(cm)	Row-Column
0	3.75	19.80	13-1
1	3.75	14.35	10-1
2	3.75	8.85	6-1
3	7.65	20.8	14-2
4	7.65	15.25	11-2
5	7.65	9.85	7-2
6	7.65	4.35	3-2
7	11.7	16.25	12-4
8	11.7	10.85	8-4
9	11.7	5.35	4-4
10	15.5	20.8	14-5
11	15.5	15.25	11-10
12	15.5	9.85	7-5
13	15.5	4.35	3-5
14	19.35	19.8	13-6
15	19.35	14.35	10-6
16	19.35	8.85	6-6
17	23.25	20.8	14-7
18	23.25	16.25	12-7
19	23.25	11.85	9-7
20	23.25	6.35	5-7
21	27.15	19.8	13-8
22	27.15	14.35	10-8
23	27.15	8.85	6-8
24	31.0	20.8	14-9
25	31.0	15.25	11-9
26	31.0	9.85	7-9
27	31.0	4.35	3-9
28	34.95	16.25	12-10
29	34.95	10.85	8-10
30	34.95	5.35	4-10

TC #	x(cm)	y(cm)	Row-Column
31	38.75	20.8	14-11
32	38.75	15.25	11-11
33	38.75	9.85	7-11
34	38.75	4.35	3-11
35	42.65	19.8	13-12
36	42.65	14.35	10-12
37	42.65	8.85	6-12
38	46.55	20.8	14-13
39	46.55	16.25	12-13
40	46.55	11.85	9-13
41	46.55	6.35	5-13
42	50.45	19.8	13-14
43	50.45	14.35	10-14
44	50.45	8.85	6-14
45	54.3	20.8	14-15
46	54.3	15.25	11-15
47	54.3	9.85	7-15
48	3.75	1.35	1-1
49	58.2	16.25	12-16
50	58.2	10.85	8-16
51	11.7	19.8	13-4
52	62.05	20.8	14-17
53	62.05	15.25	11-17
54	62.05	9.85	7-17
55	62.05	4.35	3-17
56	65.95	19.8	13-18
57	65.95	14.35	10-18
58	65.95	8.85	6-18
59	8.75	1.35	1-3
60	19.35	3.4	2-6
61	27.15	3.4	2-8

Cell Packing:

The five initial experiments were carried out in a cell vibro-packed with 20-30 mesh Ottawa sand, giving it a permeability of 120 darcies. However, the production rates were very low and, to shorten the time required for each run, the sand for Runs 2.2 to 2.16 was replaced with vibro-packed 1mm glass beads. Data for the scaled model and the glass beads packing are summarized in Table 3.1.2.

TABLE 3.1.2
Data on Vapex Cell and its Packing

Cell inside dimensions (HxWxD)	21.7 x 69.8 x 3.5 cm
Diameter of packing beads	1 mm
Density of packed beads	1.327 kg/litre
Packing permeability	1150 darcy
Packing porosity	0.391
Number of thermocouples	62
Typical weight of beads	7.5 kg
Typical weight of oil	1.88 kg

Injector - Producer:

In experiments with Tangleflags (Lloydminster) heavy oil, it was advantageous to have a separate injector and producer, as illustrated in Figure 3.1.5. The injector was positioned either directly above the producer, or diagonally across the cell in the upper right hand side corner. Injector offset tends to increase the size of the vapour chamber and therefore to improve the recovery.

The use of Cold Lake bitumen in some of the later experiments required an initial communication path between the injector and the producer. This was achieved by injecting steam into double jacketed wells, such as those in Figures 3.1.6 to 3.1.8, until the pressure gradient in the cell formed a breakthrough channel alongside the heated tube and bitumen production commenced.

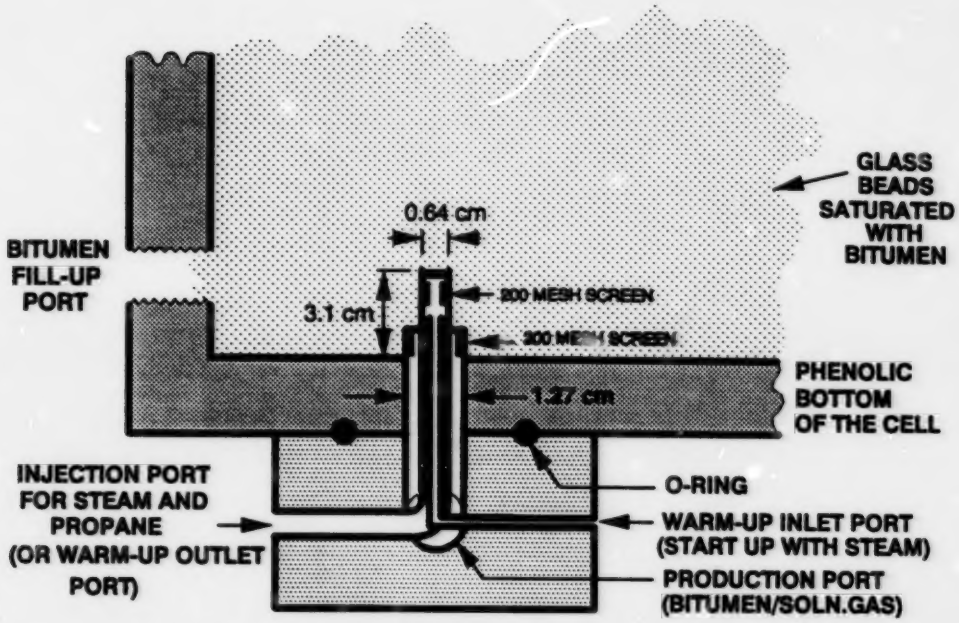


FIG.3.1.7. HEATED VAPEX INJECTOR/PRODUCER

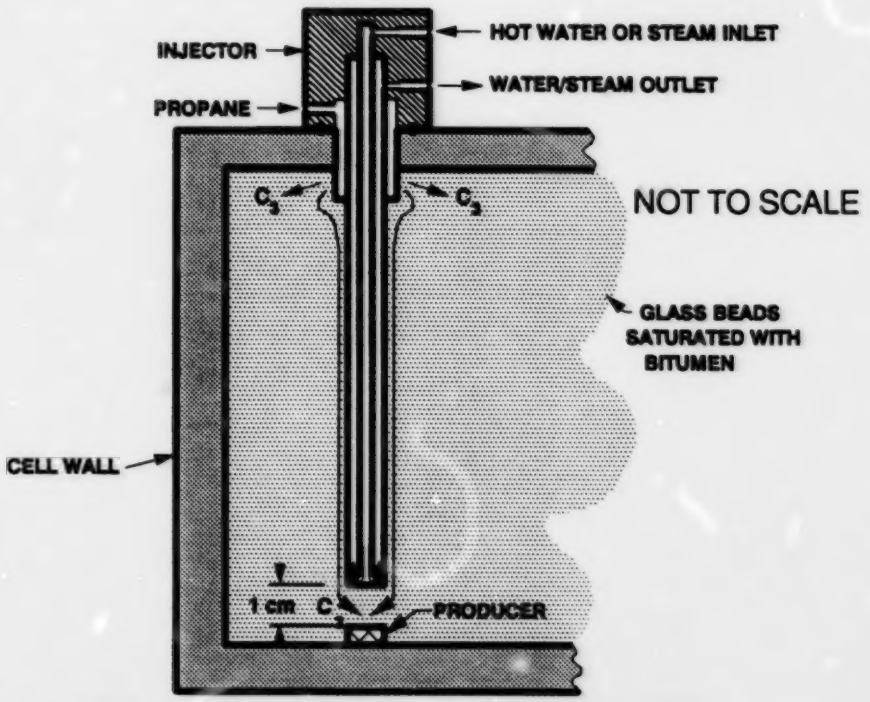


FIG.3.1.8. COLD LAKE INJECTOR

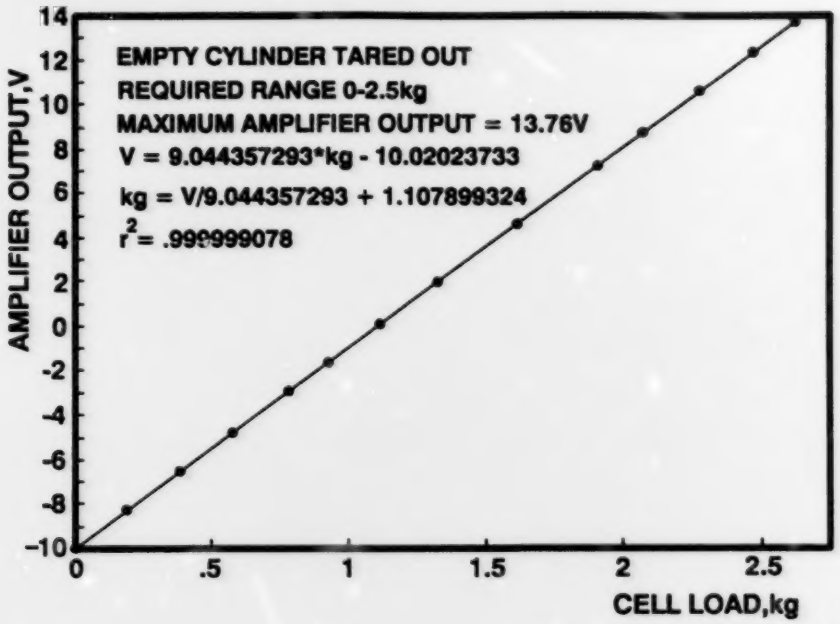


FIG.3.1.9. PROPANE LOAD CELL CALIBRATION

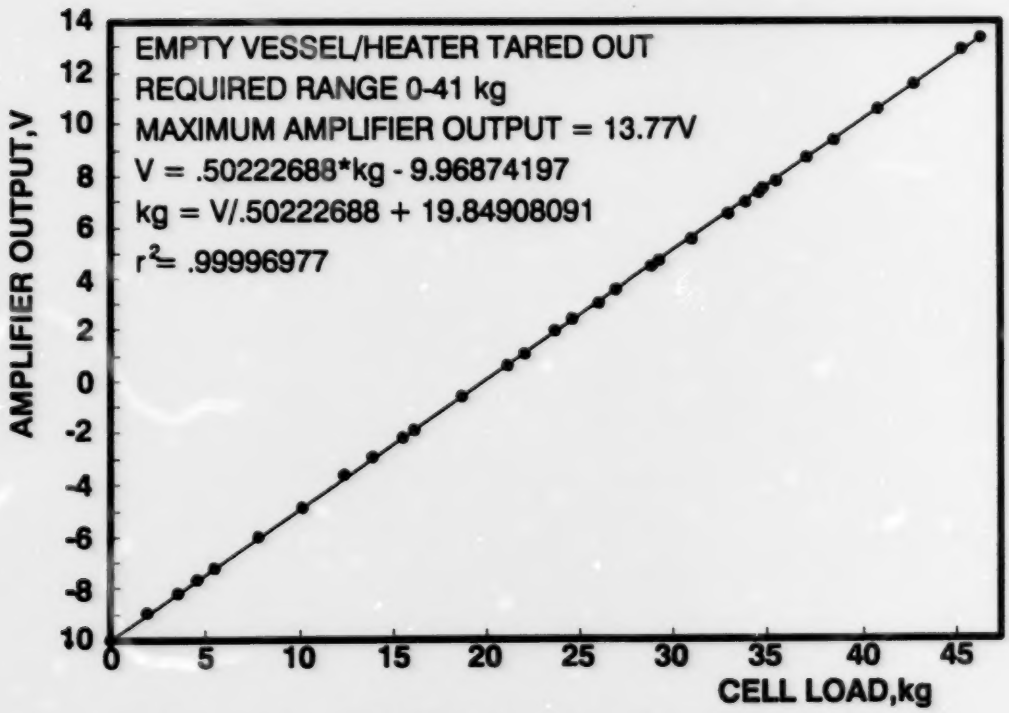


FIG.3.1.10. WATER LOAD CELL CALIBRATION

The vertical double jacketed injector/producer was used in the initial, and a modification of it, in the final experiments. Because the external warming of the length of the well affected the heat balance in the cell, this arrangement was avoided in low temperature runs and separate injection and production wells without pre-heater and with sideways injection (Fig. 3.1.5) were used instead. The length of the injector stem, and therefore the tip-to-tip distance between the injector and the producer, was varied according to the oil viscosity to facilitate an early breakthrough.

Pumps and Dampener:

Figure 3.1.3 shows schematically the pumping arrangement. Hot water and liquid propane were metered individually by two Pulsa Series diaphragm pumps and the high pressure steam required in some experiments was produced in a steam generator located behind the pressure vessel. A knock-out pot (Fig. 3.1.2) inside the pressure vessel ensured the removal of the condensate from the steam so that only dry steam was injected into the cell. The propane pump used was a Pulsafeeder Model 7120-S-AE, flat diaphragm metering pump, 0 to 2.3 US GPM at 2000 psig, with a Pulsamatic 2VADDB electric stroke length control actuator. The water pump was a Pulsafeeder Model 7120-S-AE flat diaphragm metering pump, 0 to 6.8 US GPM at 1200 psig maximum discharge pressure with a Pulsamatic 2VADDB electric stroke length control actuator. Both pumps were made by Pulsafeeder of Rochester, N.Y.

To dampen any sudden pressure surges, a Greer Model 806100 pulsation dampener was connected in line with the pumps. This dampener was rated for 2000 psig and was precharged to 80% of its working pressure. The pumping stroke of the pumps was actuated by an electric signal from a pressure transducer (Taylor 400 T series) or a thermocouple, and the automatic control was maintained by two Taylor Microscan 500 PID process controllers (Model 500RB1004A).

Load Cells and Amplifiers:

For the purpose of material balance, both the injected hot water and propane were weighed by two independent load cells. The collected water-oil samples contained

emulsions and were therefore analyzed by Karl-Fischer method for water to determine the amount of oil recovered; the volume of produced solution and free propane gas was measured in gas collectors of the separator and mass balanced against the injected gas.

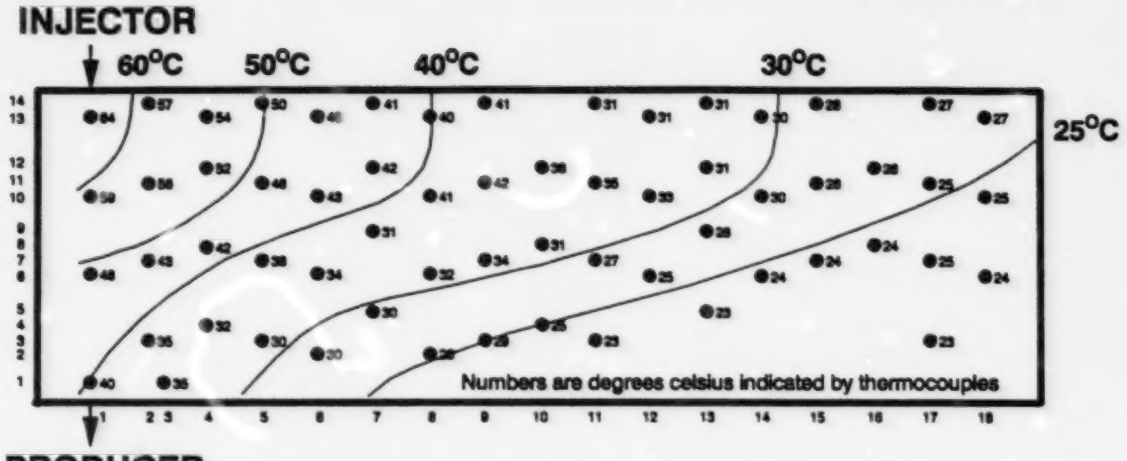
The amplifier circuits for the load cells were built in-house (Appendix I). The load cell outputs were connected to the two remaining Taurus terminals and a Basic program written for that purpose (Appendix II) directed the Taurus/PC data acquisition system to scan the 62 thermocouples and read the load cells at predetermined intervals of time. The amplifiers for the load cells were designed so that their response to load be linear over the range of measurement. Calibration curves to confirm this experimentally are given in Figs. 3.1.9 and 3.1.10 and the correlation equations obtained in this way were incorporated in the computer program to calculate the injection rates.

Screen Display:

The temperatures read by the Taurus/PC were displayed on the CRT screen to produce the true image of the cell with the thermocouples in their actual location. At the same time, the load cell weights were used to calculate and display the instantaneous rates of water and propane injection. The temperatures, initial weights, final weights and injection rates were also recorded on file. The temperature and weight data were used in determining the extent of the solvent chamber advance with time and in evaluating the production performance.

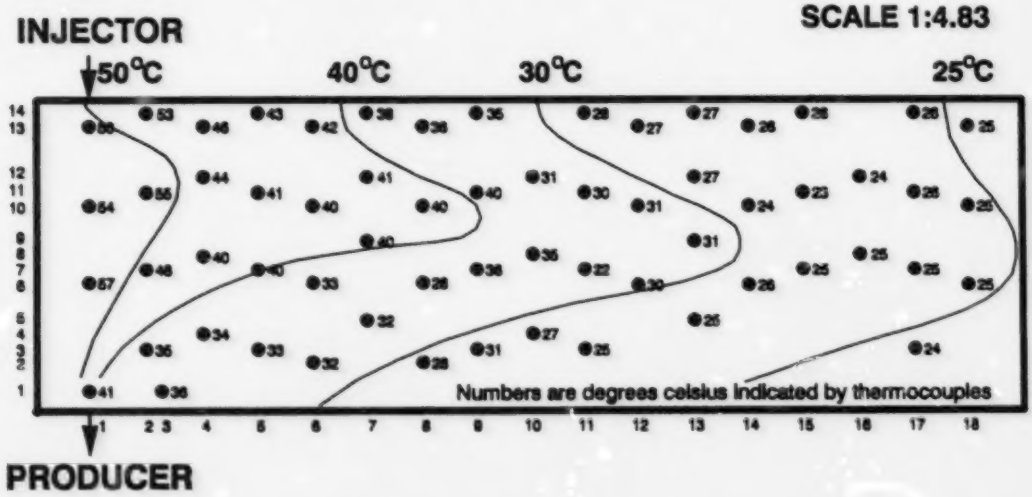
Examples of using thermocouple data to visualize heat transfer away from the plane of injector and producer are given in Fig. 3.1.11 for an experiment performed on Dec. 7, 1990. The drawings show an advancing heat front at 4 and 7 hours of experimental time. The shape of the isotherms is largely determined by experimental conditions. This data maps the shape, and tracks the rate of lateral spread, of the vapour chamber. The final shape and size of the chamber was confirmed at the end of the run when the cell was opened, examined and photographed.

SCALE 1:4.83



DATE: DECEMBER 7,1990
TIME FROM START: 4 hrs
PRESSURE: 180 psig

SCALE 1:4.83



DATE: DECEMBER 7,1990
TIME FROM START: 7 hrs
PRESSURE: 200 psig

VAPEX: SPREADING HEAT FRONT IN THE PHYSICAL MODEL

FIG.3.1.11

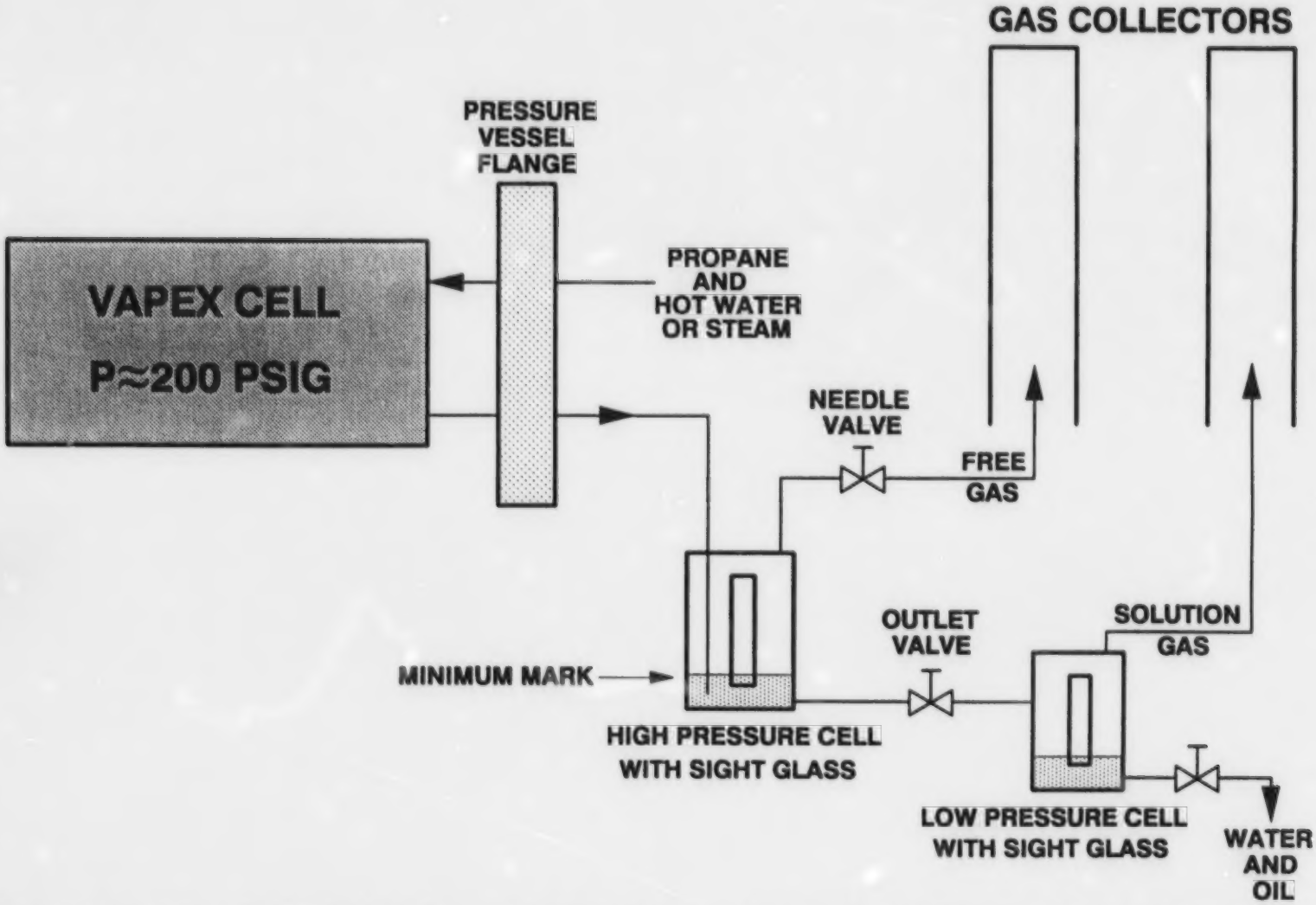


FIG.3.1.12. DIAGRAM OF THE OIL-WATER-GAS SEPARATOR

Separator:

A schematic diagram of the gas/water and oil separator is given in Fig. 3.1.12. It was designed in a way that made it possible for both free and solution gas to be measured individually. The high pressure cell contains free gas which is bled off at a very low rate through a fine needle valve. The liquid level in the high pressure cell, as viewed through the sight glass, was maintained above a minimum mark by adjusting the outlet valve. The solution gas was allowed to flash in the low pressure vessel and was collected separately. The gases were then combined, their volumes converted into mass and compared with the liquid propane injected. Any inconsistencies resulting from leaks were investigated and corrected. The remaining liquid effluent containing water, oil and emulsions was then collected in weighed jars and analysed for water content by the Karl-Fischer method to determine the amount of oil produced in a given time interval.

Calibration:

We have encountered considerable difficulties with the Pulsafeeder diaphragm metering pump for water. The pump had a tendency to deliver lower volumes at high pressures. After repeated shutdowns and many local repairs, the pump had to be eventually crated and shipped back to the manufacturer for a replacement of faulty parts under warranty. This delay created a substantial setback in our timetable for the experimental work. After the repair, the delivery rates were extensively tested at different pressures and pumps calibrated (Figs. 3.1.13 and 3.1.14). It appears that the problem has been solved.

With the experimental conditions near to, but not at, the propane dew point, it was important that the thermocouple readings be accurate. The 62 thermocouples were connected to two Taurus buses functioning independently. The buses were adjusted internally to ensure their balanced operation and the thermocouples were then calibrated against an external heat source. The results are plotted in Fig. 3.1.15 over the required temperature range of 20-80°C. The dotted line represents a temperature as indicated by a mercury-in-glass thermometer (i.e., 20 to 80°C in 10 degree increments). Superimposed is a set of experimental temperatures indicated by thermocouples 0 to 61.

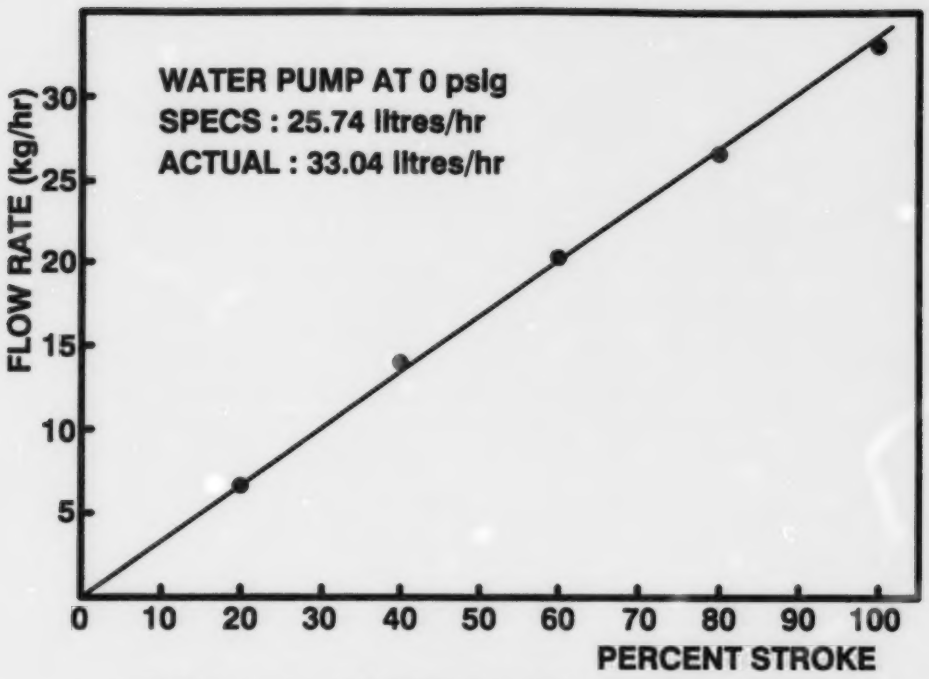


FIG.3.1.13. WATER PUMP CALIBRATION

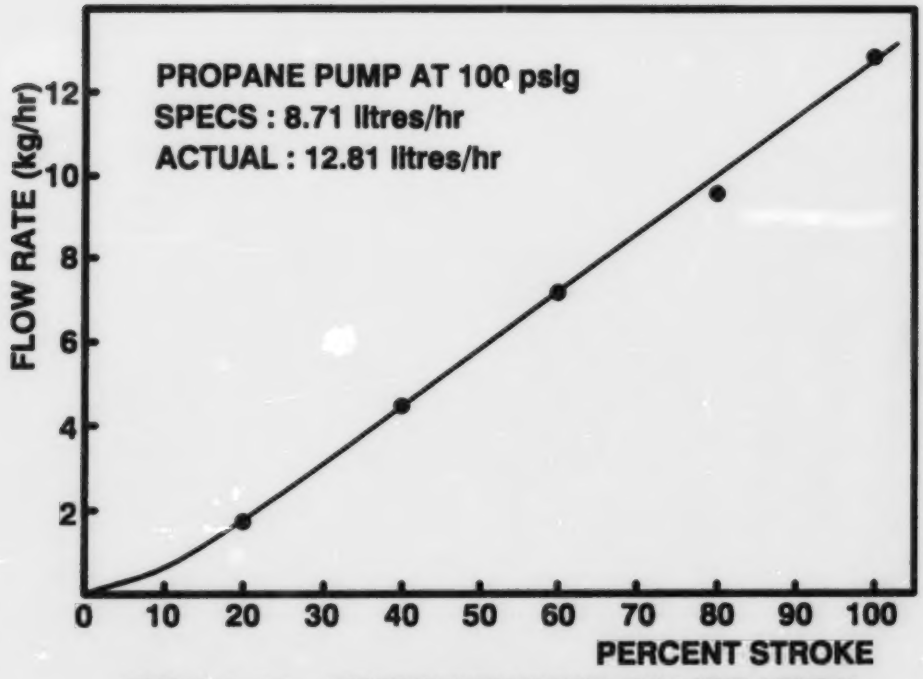
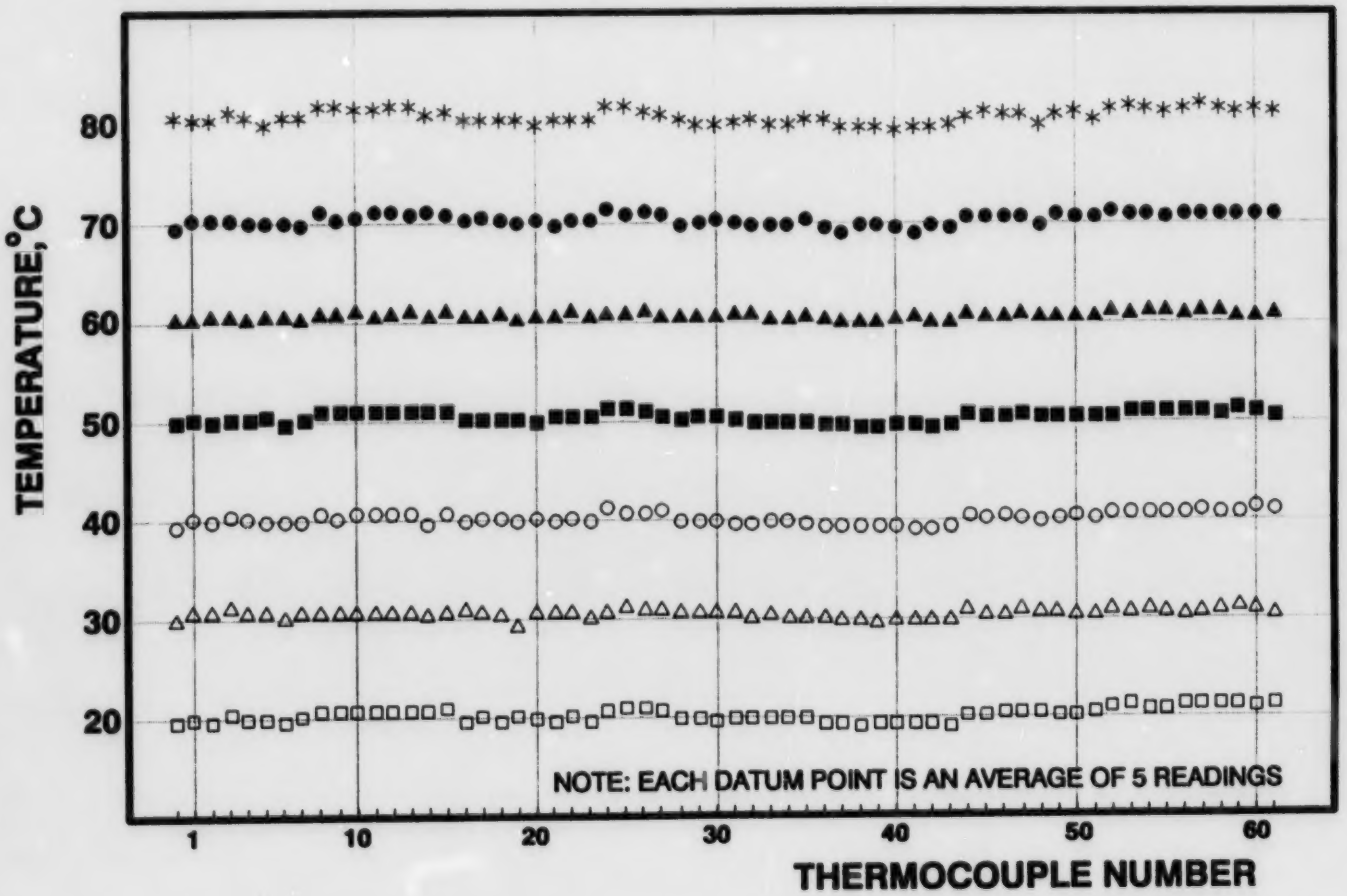


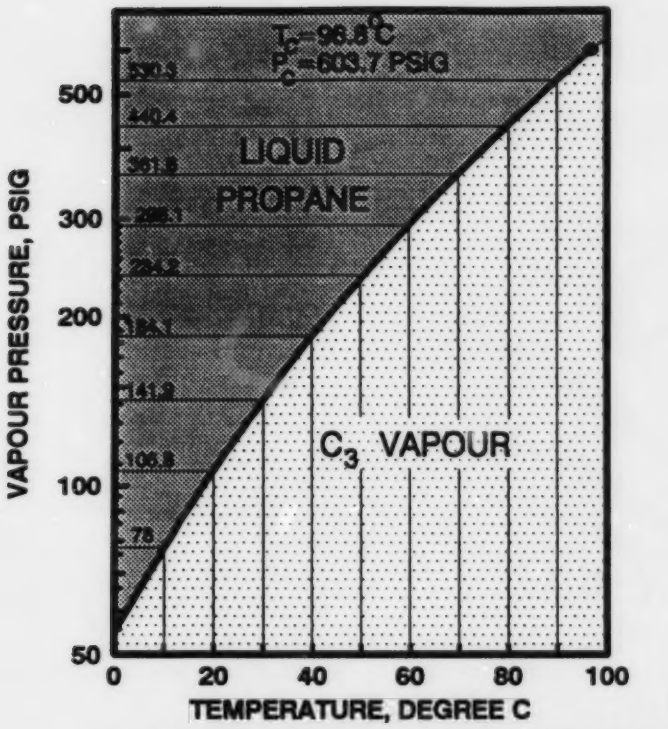
FIG.3.1.14. PROPANE PUMP CALIBRATION

CALIBRATION TESTS OF THERMOCOUPLES



TEMPERATURES INDICATED BY THERMOCOUPLES AT 20(□), 30(△), 40(○), 50(■), 60(▲), 70(●) AND 80(✳) °C

FIG 3.1.15



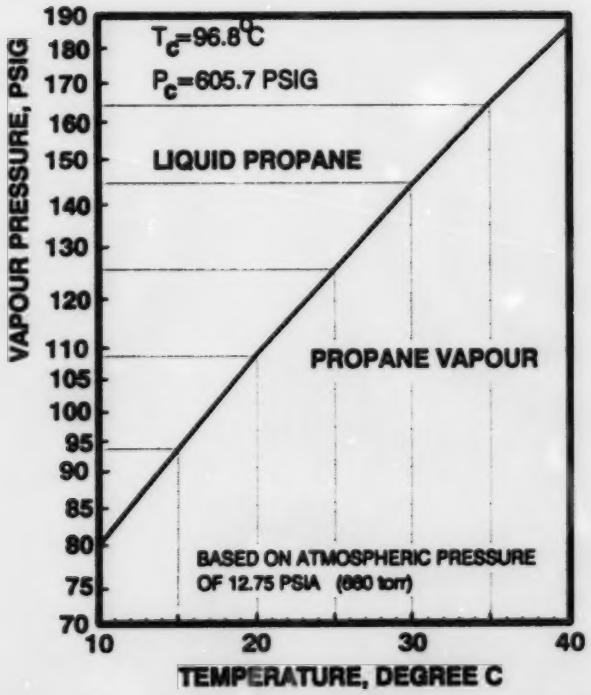


FIG.3.1.16. VAPOUR PRESSURE OF PROPANE

Each plotted point is an average of 5 readings. As can be seen, the thermocouple readings are within about one degree of the true temperature.

Vapour Pressure:

Figures 3.1.16 and 3.1.17 are vapour pressure curves for pure propane and ethane. The data were calculated from the Antoine equation and converted into gauge pressures. Both gases used in our experiments were about 99% pure and the temperature-vapour pressure plots facilitated setting and maintaining the experimental conditions during each run. Some useful information on propane and ethane is listed in Table 3.1.3 below [4]:

TABLE 3.1.3

	Propane	**Ethane**
T_c	96.8°C	32.3°C
P_c	618.4 psia	708.3 psia
ρ_ℓ at 20°C	0.5005 g/ml	0.3513 g/ml
ρ_v at 20°C and 670 torr	1.6032 g/l	1.1252 g/l
Boiling point, °C	- 42.1	- 88.6
Specific gravity (air=1)	1.52	1.03
μ_ℓ, mPas (588 psia and 20°C)	0.1045	0.0435

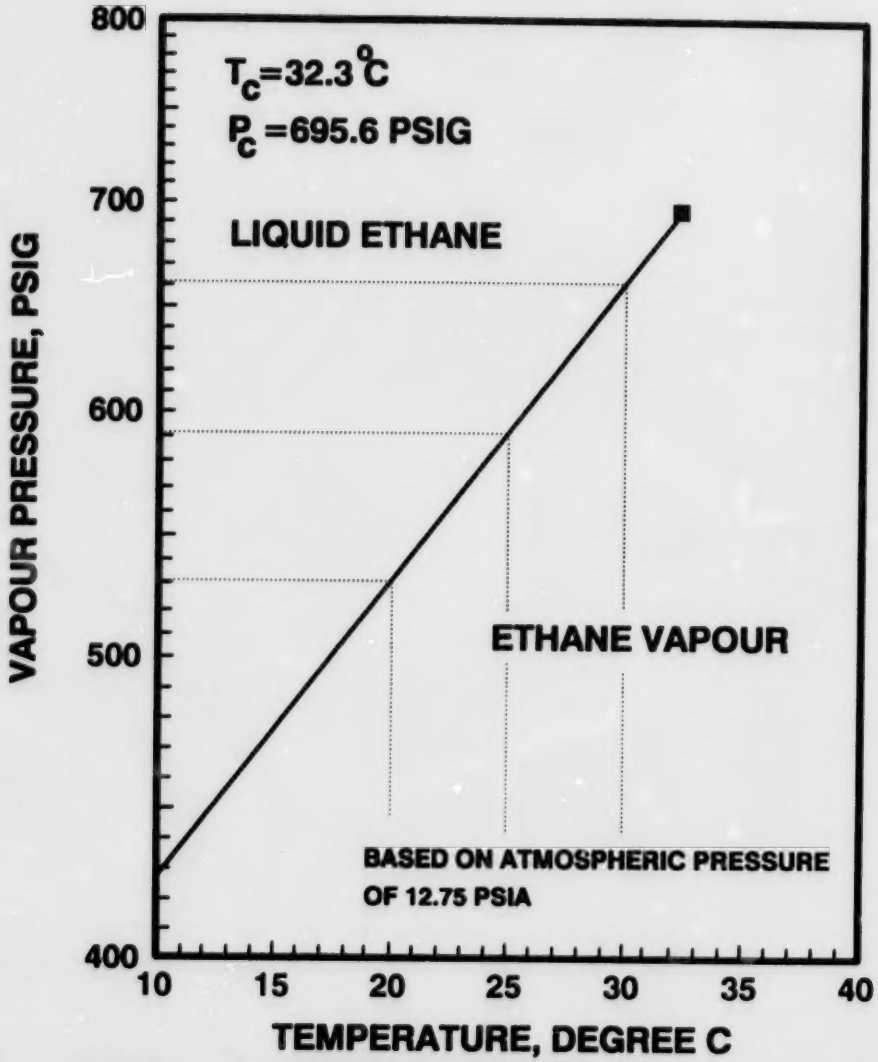


FIG.3.1.17. VAPOUR PRESSURE OF ETHANE

3.2 Phase 2 Vapex Experiments in the Scaled 2D Model: Results of 16 Runs

Summary Table:

The summary of experimental work carried out in the 2D scaled cell packed with sand or 1 mm glass beads is given in Table 3.2.1. As indicated on the production plots for individual experiments, runs 2.2 to 2.16 were performed with 1 mm glass beads packing and run 2.1 with Ottawa sand.

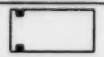
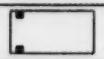
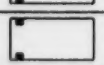
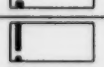
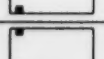
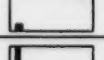
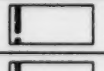
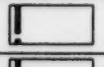
During the four preliminary runs, the proper function of the apparatus was tested and any required modifications or adjustments were carried out. In the 16 runs that followed, a development and testing of the Vapex concept was pursued.

In the first 5 experiments, the cell was filled with Tangleflags heavy oil and, following the completion of a hot water flood, propane was injected to stimulate further recovery. In the next 6 runs (2.6 to 2.11), the initial waterflood was eliminated, and saturated propane vapour (or ethane in some cases) was injected right from the start. Cell pressures were usually maintained constant for the duration of the run and the vapour chamber temperatures were allowed to raise naturally as a result of latent heat of solution of propane (or ethane) in the heavy oil (or bitumen). The objective was to ascertain the effectiveness of this method at temperatures that were only 10 - 30°C above the typical Lloydminster or Cold Lake reservoir.

In the final three experiments, saturated steam was used as a heating medium and saturated propane co-injected as an active additive. The purpose was to study the coexistence of steam and solvent vapour chambers from the temperature profile displayed on the computer CRT and their effectiveness in the recovery of the Cold Lake bitumen and Tangleflags heavy oil. The observations made will be discussed later.

The fifth column of Table 3.2.1 lists the mutual positions of the injection and production well. The early single, double-jacketed, steam heated injector (run 2.1) was replaced in favour of a separate injector and producer which proved to be an effective way of creating an initial breakthrough channel without the introduction of an unknown amount of extraneous heat.

TABLE 3.2.1: SUMMARY OF VAPEX RUNS IN PHASE 2 *

Vapex Run #	Date	Type of Oil	Solvent Gas	Well Configuration	Cell Pressure (psig)	Cell Temperature (°C)	Karl Fischer	Viscosity	Asph. Prec.	% Recov.	Total Time (hrs)
Preliminary Runs: 17.Sept.90, 28.Sept.90, 12.Oct.90 and 9.Nov.90											
2.1	90-11-29	Tanglfigs	C_3-Water		210	45	No	No	Yes	38	6
2.2	90-12-07	Tanglfigs	C_3-Water		150-230	40-50	Yes	No	Yes	61	7
2.3	91-01-09	Tanglfigs	C_3-Water		170-270	54-70	Yes	No	Yes	32	7
2.4	91-01-18	Tanglfigs	C_3-Water		200-300	50-62	Yes	No	Yes	33	10
2.5	91-02-01	Tanglfigs	C_3-Water		250	60-80	Yes	No	Yes	27	8
2.6	91-02-14	Tanglfigs	Propane		150-218	30-40	No	Yes	Yes	33	6
2.7	91-03-05	Tanglfigs	Propane		120	27-30	No	Yes	Yes	30	7
2.8	91-03-19	Tanglfigs	Propane		120	26-30	No	Yes	Yes	55	8
2.9	91-04-02	Tanglfigs	Ethane		580	24-29	No	Yes	No	20	3
2.10	91-04-11	Tanglfigs	Ethane		550	23-32	No	Yes	No	27	8
2.11	91-04-19	Tanglfigs	Ethane		570-600	21-28	No	Yes	No	20	8
2.12	91-04-30	Cold Lake	Propane		110	21-30	No	Yes	No	21	11
2.13	91-05-07	Cold Lake	Propane		120	20-30	No	Yes	No	16	7
2.14	91-06-24	Cold Lake	C_3-Steam		210	45/199	Yes	Yes	Yes	25	7
2.15	91-07-26	Cold Lake	C_3-Steam		210	45/199	Yes	No	No	23	7
2.16	91-08-09	Tanglfigs	C_3-Steam		210	45/199	Yes	Yes	Yes	40	7

*Detailed data are given in Figs.3.2.1-3.2.16, eg. for Run 2.1, see Fig. 3.2.1

The injector-producer pair was first positioned directly above each other. In later experiments with the Tangleflags heavy oil, the wells were staggered to improve the sweep efficiency and create a large vapour chamber right after the initial breakthrough. However, due to the higher viscosity of the Cold Lake bitumen, the well positions had to be reverted to the initial configuration (ie., directly above each other) with a tip-to-tip distance of about 5 mm.

The 8th and 9th columns document whether the Karl-Fischer analysis for water was carried out and whether the viscosity of collected samples was measured. It was usually very difficult to carry out both these measurements on the same sample reliably.

The last 3 columns of Table 1 deal with asphaltene precipitation and the cumulative oil recovery at the end of the experiment.

Scaling Parameters:

In our previous work [2,3] we derived scaling equations which can be used to predict the performance of the process in the reservoir. The extent of asphaltene precipitation in the field is assumed to be the same as in the cell and, as a result, the effect of reduced permeability and viscosity cancels in the equations.

The model (M) and field (F) parameters are summarized below:

k_M = 1150 darcy $\quad k_F$ = 5 darcy

ϕ_M = 0.391 $\quad \phi_F$ = 0.35

$(\Delta S_o)_M$ = 0.86 $\quad (\Delta S_o)_F$ = 0.86

H_M = 0.217 m

W_M = 0.698 m

Model depth = 0.035 m

The equivalent reservoir height H_F can be calculated from equation (1).

$$\frac{H_F}{H_M} = \left(\frac{k}{\phi^2 \Delta S_o}\right)_M \Big/ \left(\frac{k}{\phi^2 \Delta S_o}\right)_F \qquad (1)$$

which results in H_F = 40 m.

The time scaling condition was defined as [2,3]

$$\left(\frac{\phi t}{H^2}\right)_M = \left(\frac{\phi t}{H^2}\right)_F \qquad (2)$$

For this case, it predicts that 1 model hour equals 4.33 years in the field, ie.

$$1\ \mathrm{hr_M} = 4.33\ \mathrm{yrs_F} \qquad (3)$$

For example, if the oil production rate from the laboratory model, as a result of propane injection, is 155 g/hr (~ 155 mℓ/hr), then, using equation (3) and H_F = 40 m, the model production in m^3 per 1 m of a horizontal well is:

$$155\ \frac{\mathrm{cm_M^3}}{\mathrm{hr_M}} \cdot \frac{1}{3.5\,\mathrm{cm_M}} = 44.29\ \frac{\mathrm{cm_M^2}}{\mathrm{hr_M}} = 0.004429\ \frac{\mathrm{m_M^2}}{\mathrm{hr_M}}$$

Substituting for 1 model hour from equation (3) and considering that 0.217 m_M is equivalent to 40 m_F, the equivalent field production, draining from one side, per foot of well, is:

$$0.004429\ \frac{\mathrm{m_M^2}}{4.33\mathrm{yrs_F}} \cdot \frac{40^2}{0.217^2} \cdot \frac{\mathrm{m_F^2}}{\mathrm{m_M^2}} \cdot \frac{1}{365} \cdot \frac{0.3048}{0.159} = 0.1825\ \frac{\mathrm{bbl}}{\mathrm{ftd_F}}$$

Injection of propane into a 1500 ft (457 m) horizontal well drilled at the bottom of a 40 m pay zone would result in a recovery of about 548 bbl of heavy oil per day (drainage from both sides of the well).

Since the rate is approximately proportional to the square root of the drainage height [5], ie.

$$\frac{R_1}{R_2} = \sqrt{\frac{H_1}{H_2}} \qquad (4)$$

this result can be adjusted to other payzone thicknesses. For example, the rate of oil production from a 1500 ft horizontal well drilled at the bottom of a 10 m pay zone then is 274 bbl/day. Also, for this comparison, 1 hr of laboratory time becomes equal to 4.33 x $(10/40)^{1.5}$ = 0.54 years in the field, i.e., for a 10 m payzone thickness

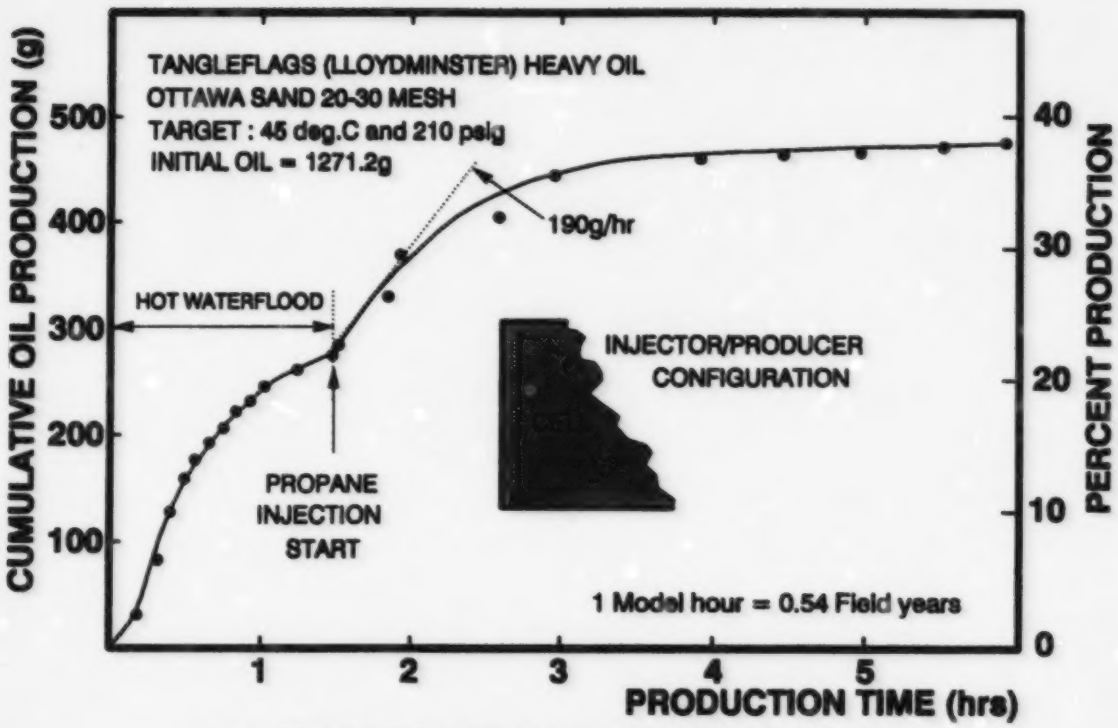
$$1\ hr_M = 0.54\ yrs_F \qquad (5)$$

These equations were used to estimate field production rates from the scaled laboratory model and the results are presented in the production plots for the individual experiments.

Presentation of Results:

Each run is summarized on a single page and is identified both by date and run number (eg. Run 901129 is Vapex Run 2.1). A photograph of the cell, opened at the end of the run, is attached at the bottom of the page. Some of these photographs were taken the following morning and changes in the distribution of oil may have occurred overnight. This will be pointed out where it is thought to be relevant. The insets contain G/O and W/O ratios and, wherever it was measured, the produced dead oil viscosity as a function of oil production. Each figure also indicates the well configuration used in the run; Table 3.2.1 serves as an index to these figures. These experimental results are discussed in Section 5.

Some photographs contain pieces of white string. These were added to accentuate the often diffused boundaries between individual regions, eg., between the region of original saturation and the vapour chamber, or, in some cases, to encircle an area where the beads were found to be consolidated.



OIL PRODUCTION FOR RUN 901129

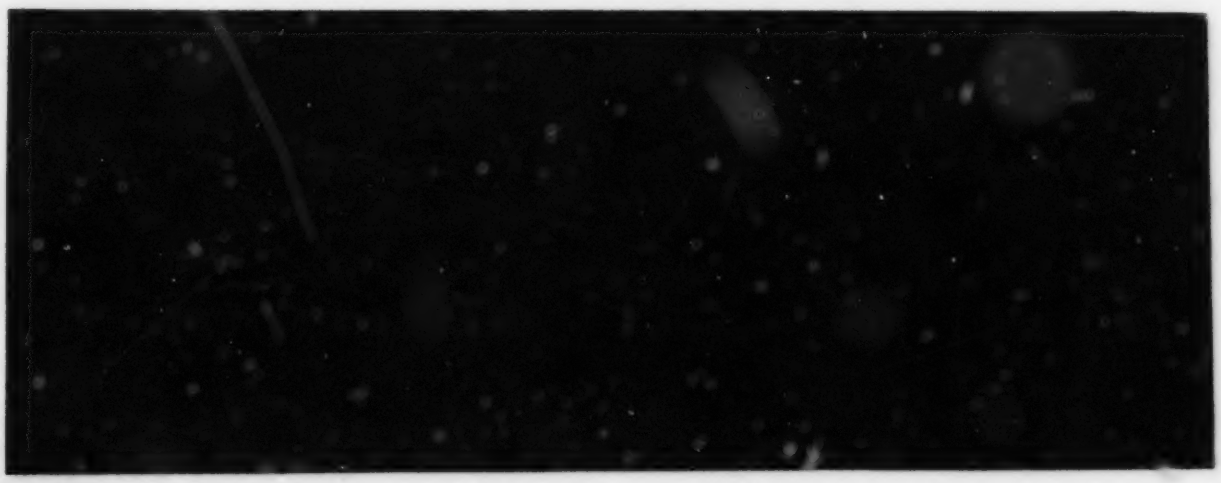
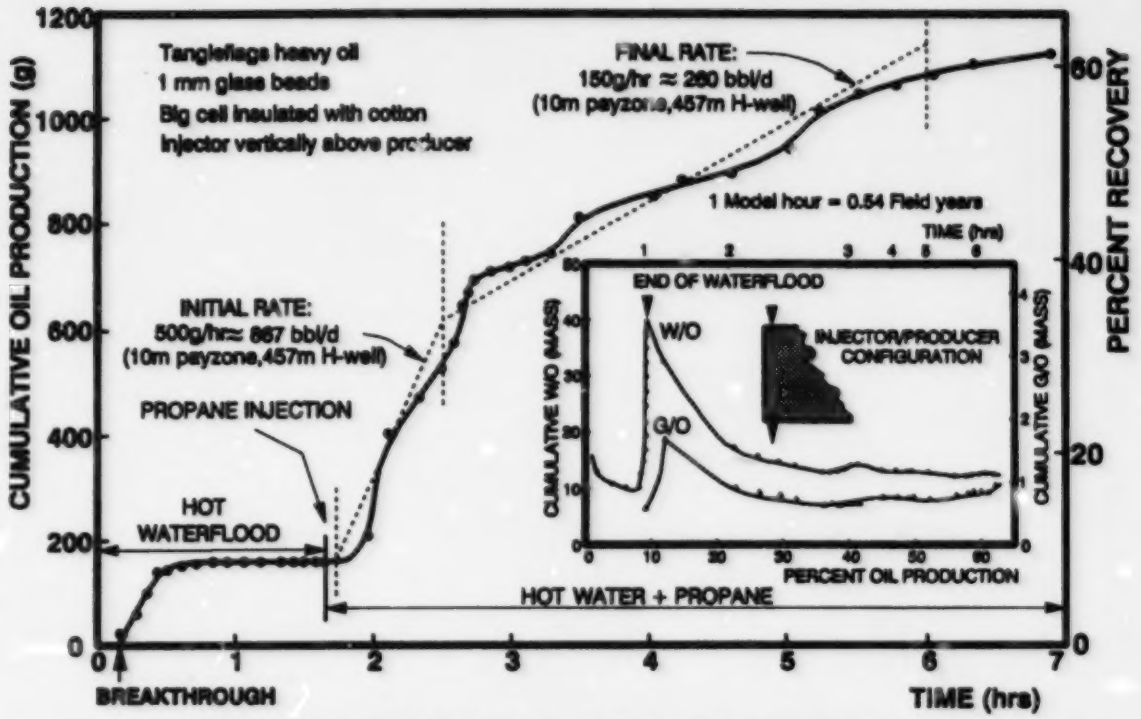


FIG.3.2.1. EXPERIMENTAL RESULTS OF VAPEX RUN 2.1



OIL PRODUCTION FOR RUN 901207

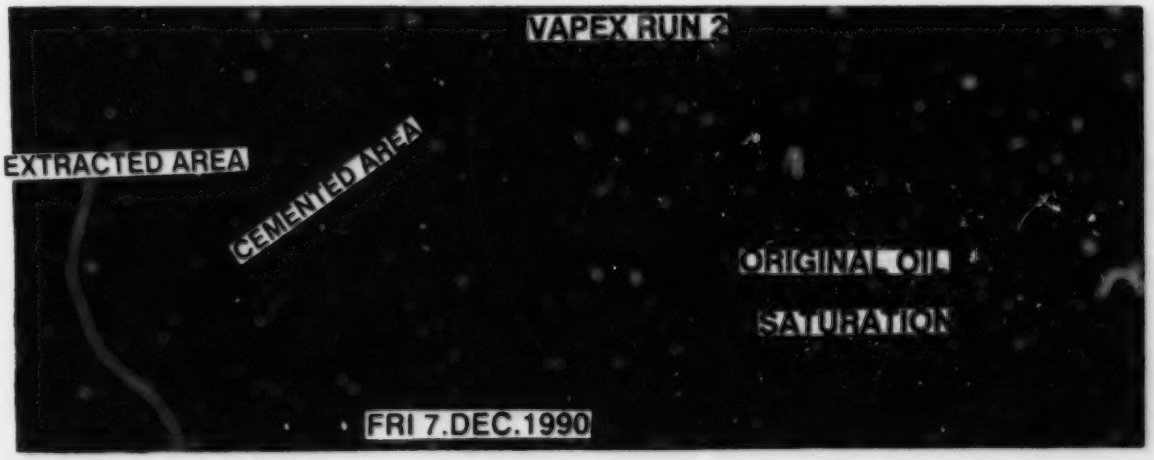
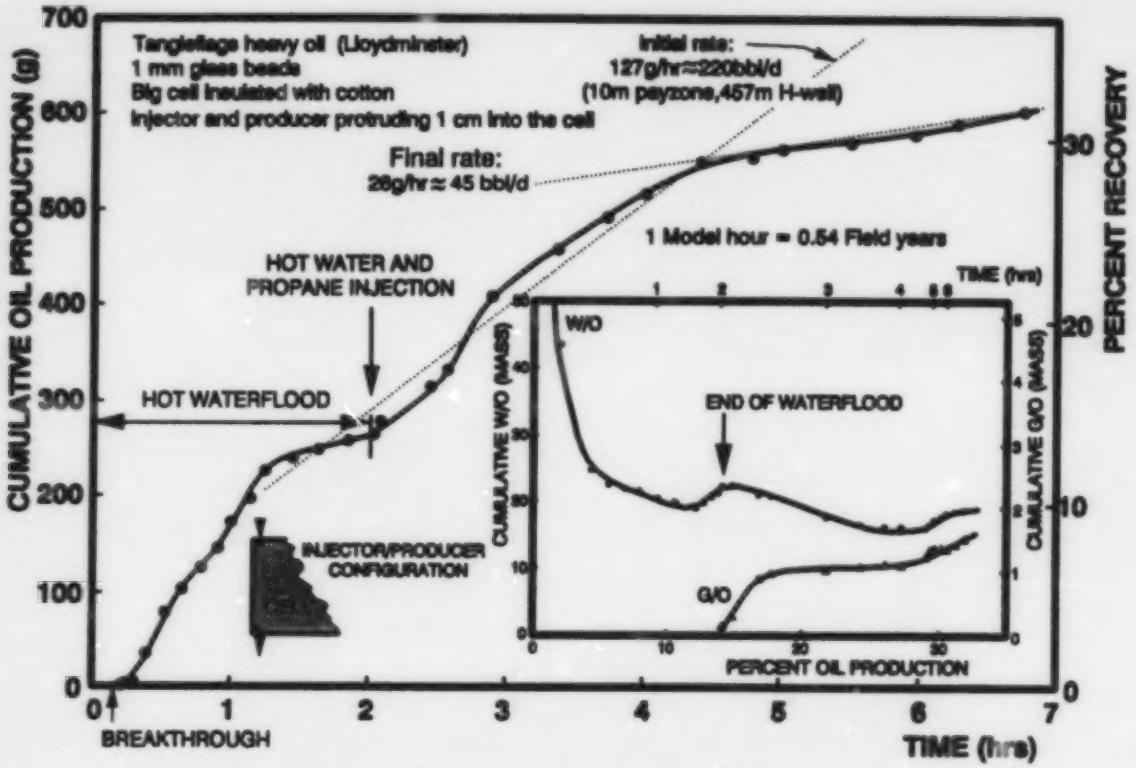


FIG.3.2.2. EXPERIMENTAL RESULTS OF VAPEX RUN 2.2



OIL PRODUCTION FOR RUN 910109

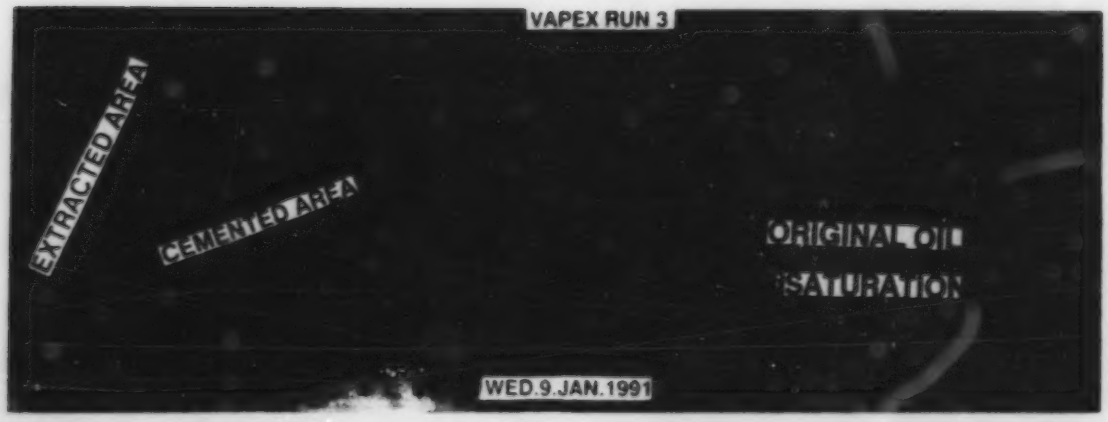
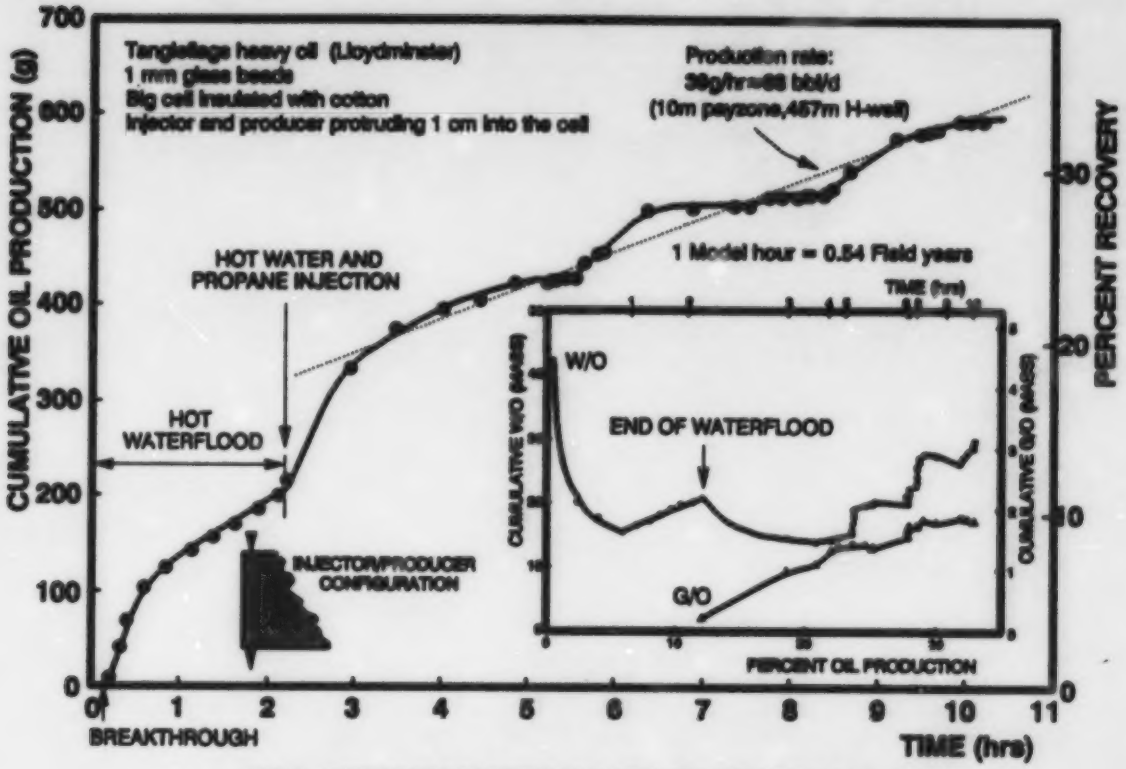


FIG.3.2.3. EXPERIMENTAL RESULTS OF VAPEX RUN 2.3



OIL PRODUCTION FOR RUN 910118

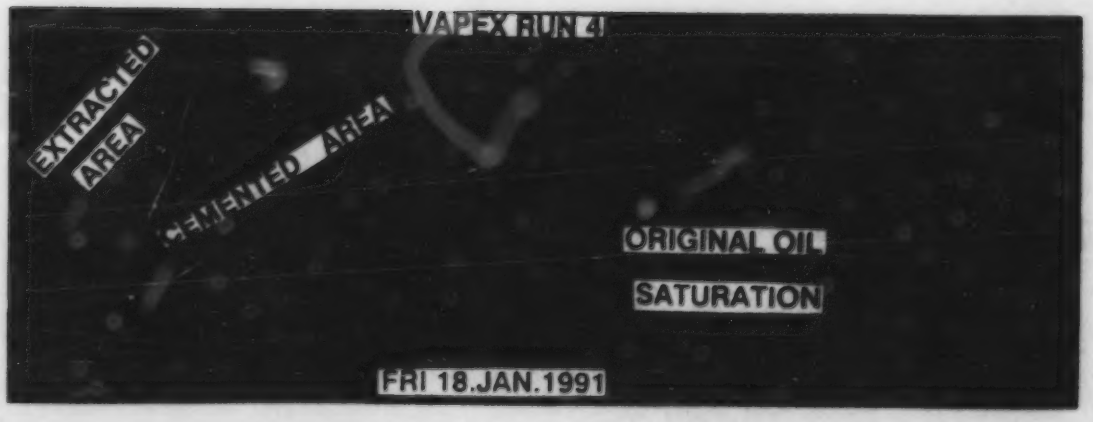
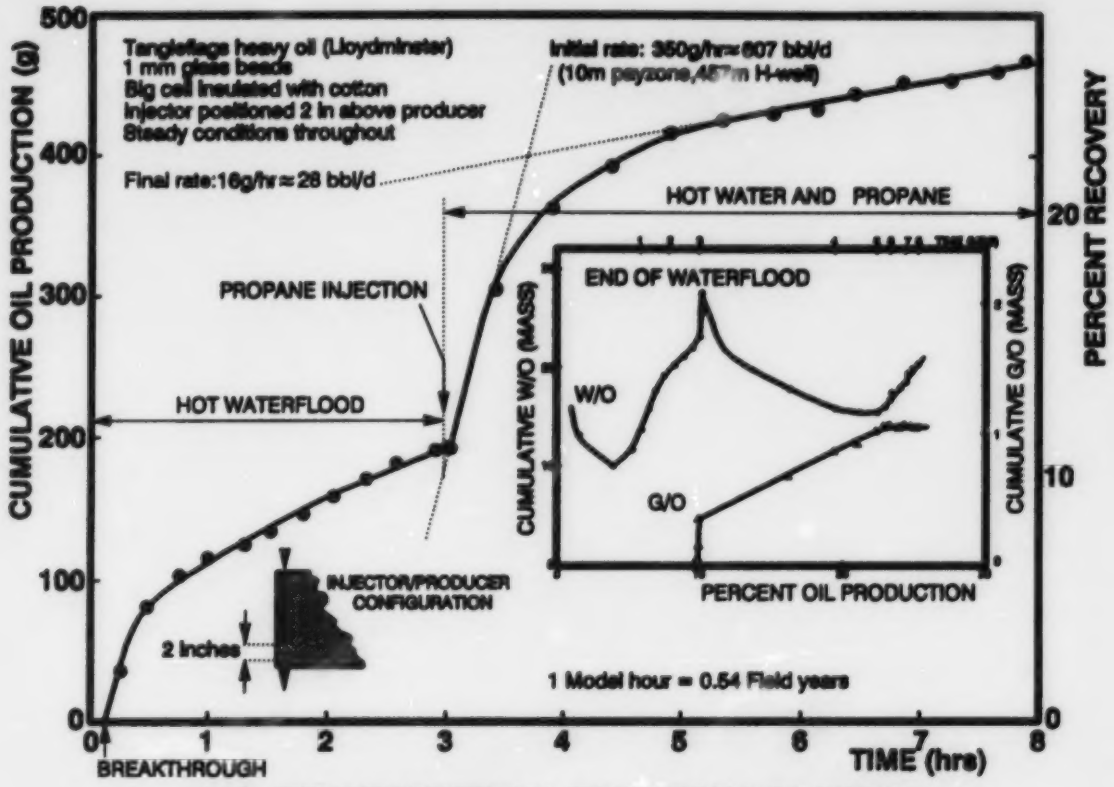


FIG.3.2.4. EXPERIMENTAL RESULTS OF VAPEX RUN 2.4



OIL PRODUCTION FOR RUN 910201

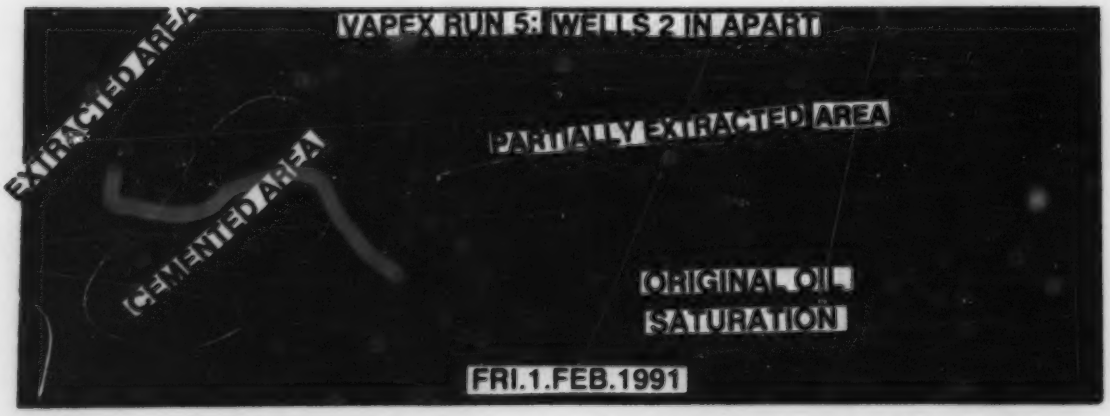
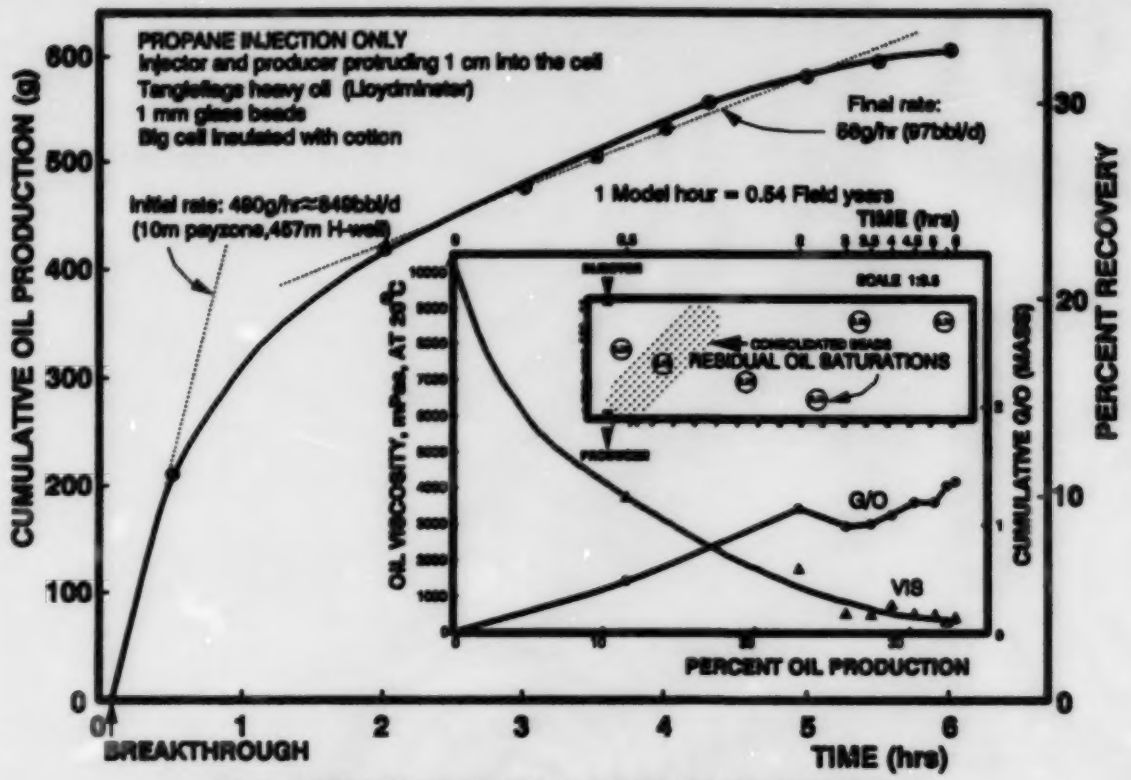


FIG.3.2.5. EXPERIMENTAL RESULTS OF VAPEX RUN 2.5



OIL PRODUCTION FOR RUN 910214

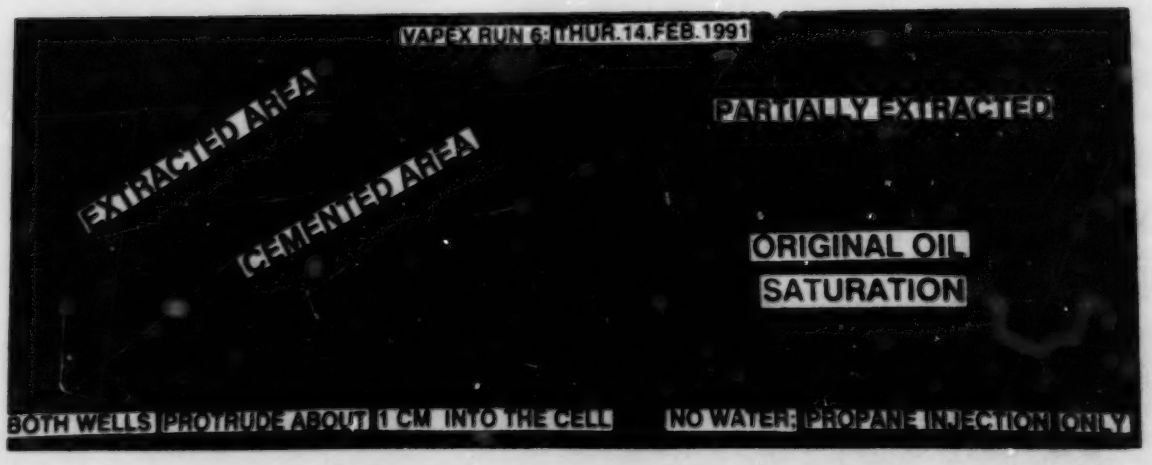
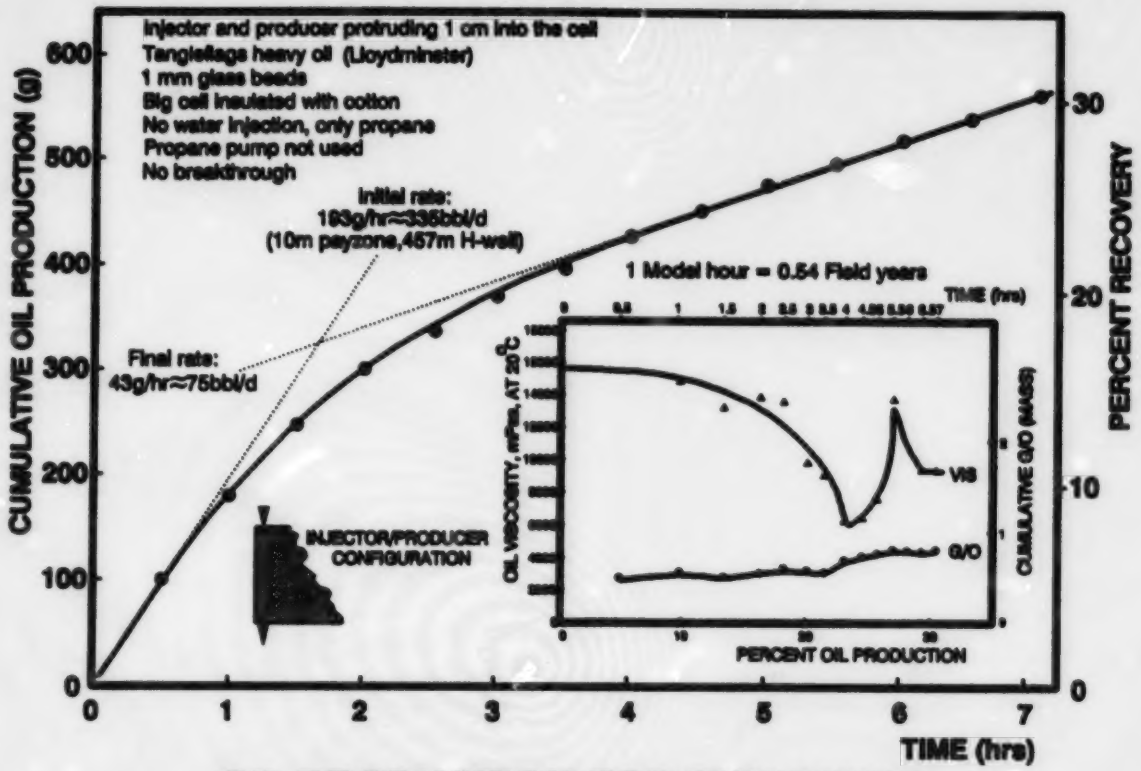


FIG.3.2.6. EXPERIMENTAL RESULTS OF VAPEX RUN 2.6



OIL PRODUCTION FOR RUN 910305

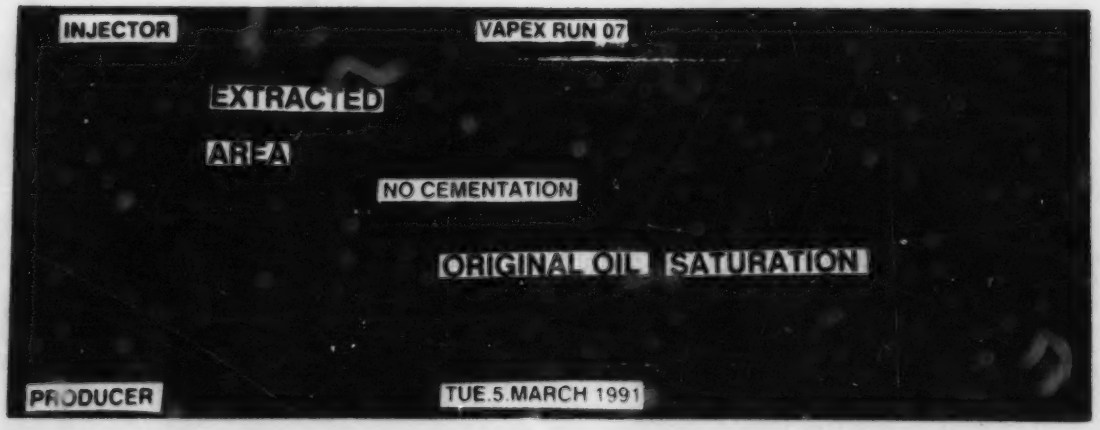
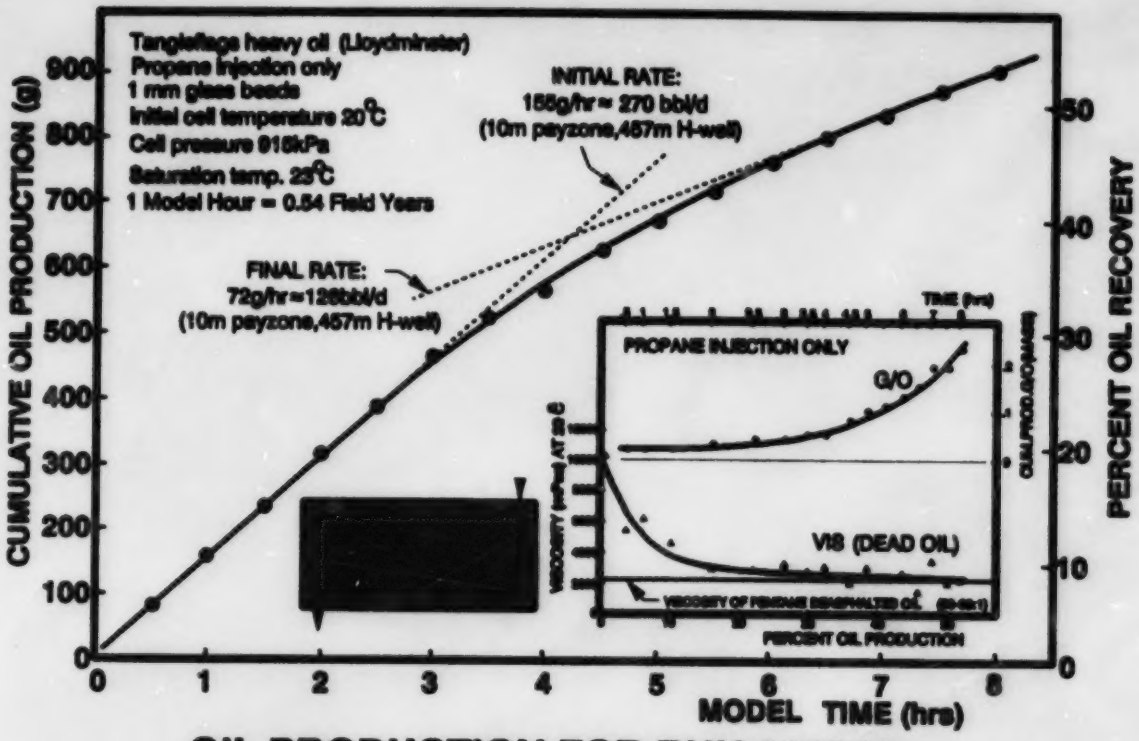


FIG.3.2.7. EXPERIMENTAL RESULTS OF VAPEX RUN 2.7



OIL PRODUCTION FOR RUN 910319

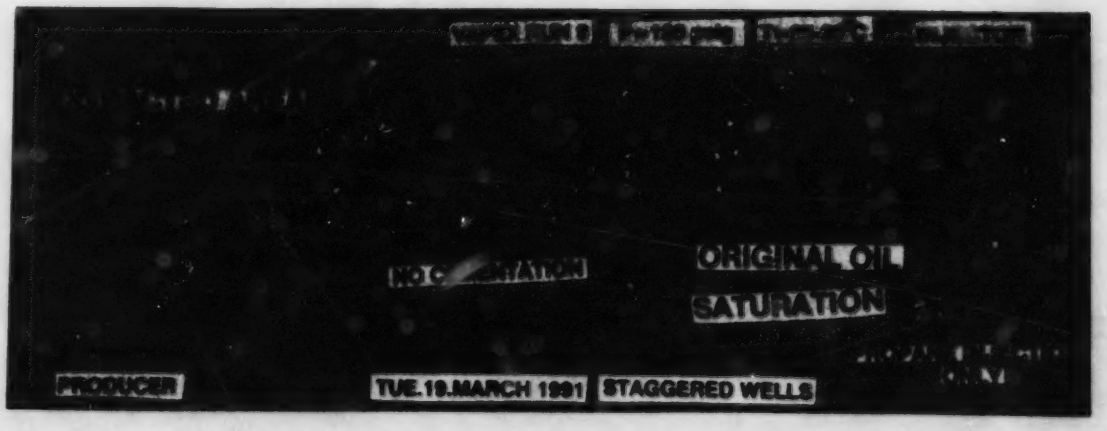
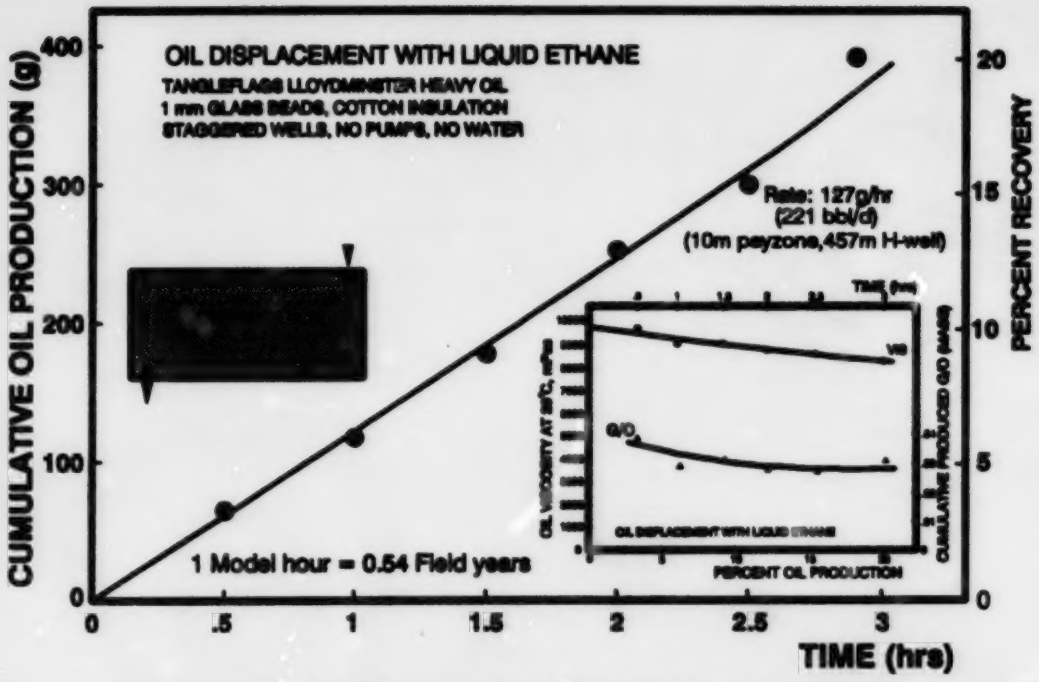


FIG.3.2.8. EXPERIMENTAL RESULTS OF VAPEX RUN 2.8



OIL PRODUCTION FOR RUN 910402

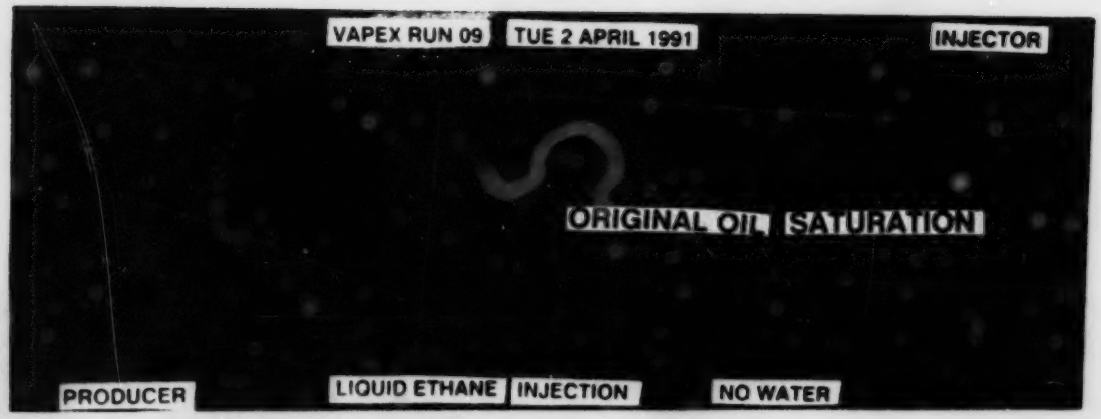
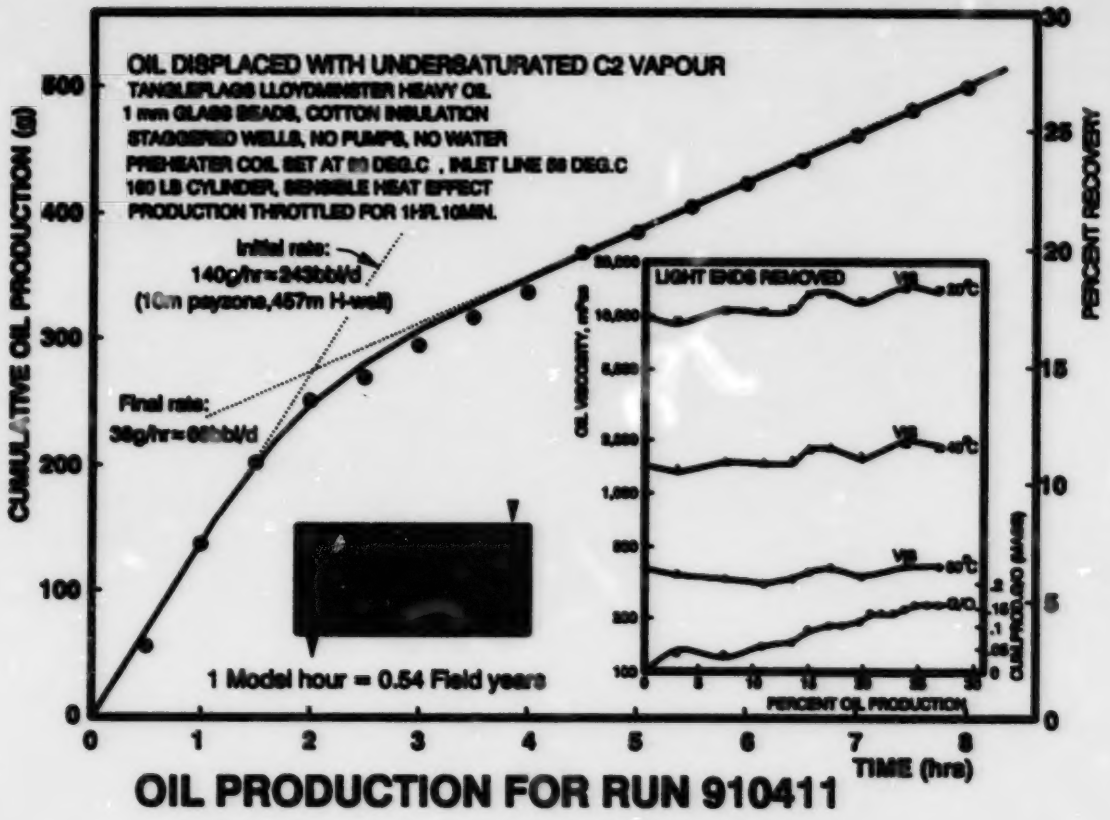


FIG.3.2.9. EXPERIMENTAL RESULTS OF VAPEX RUN 2.9



OIL PRODUCTION FOR RUN 910411

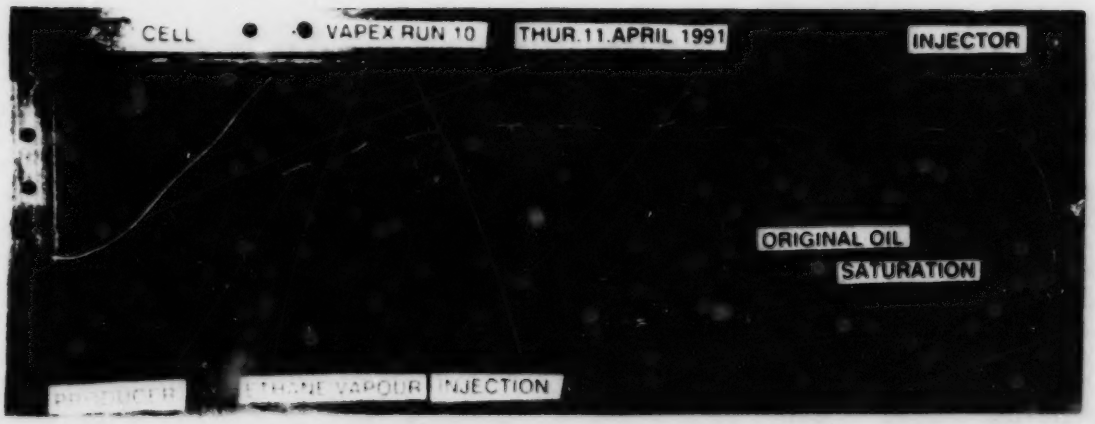
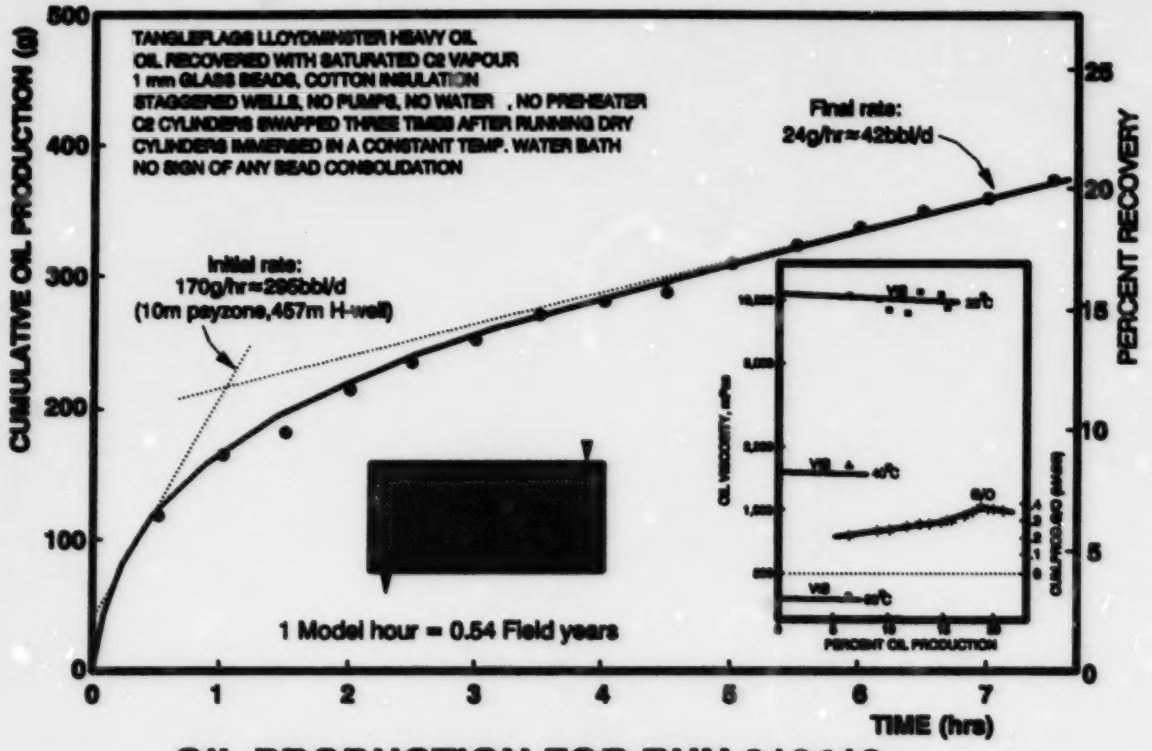
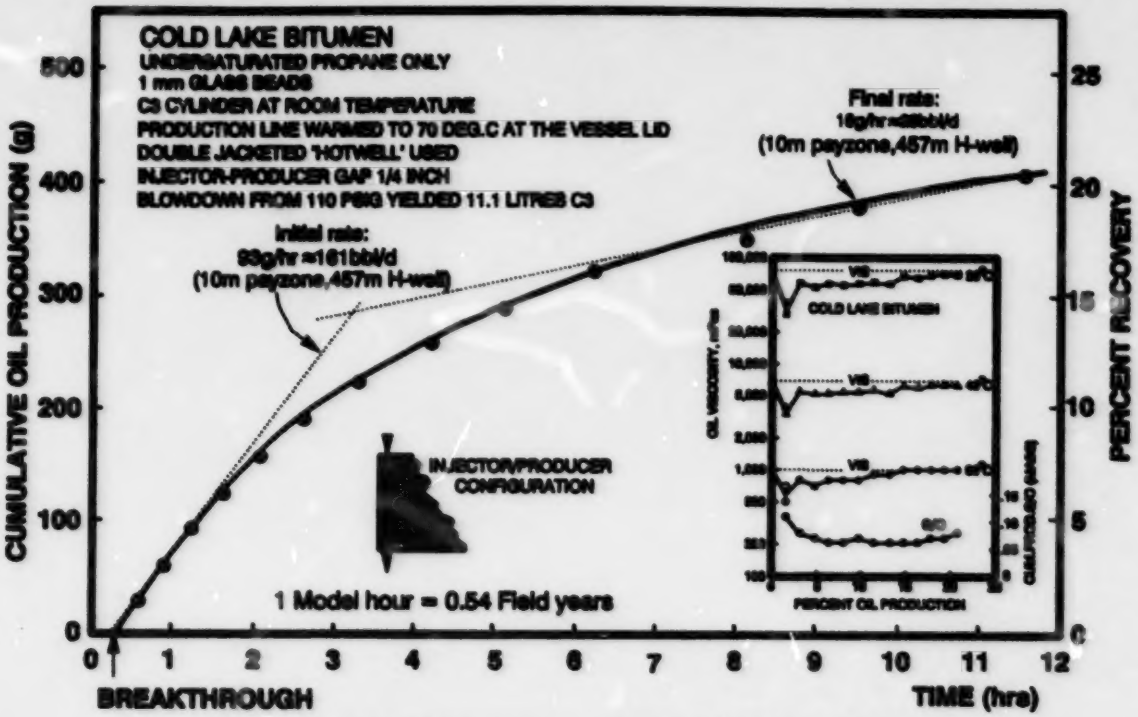


FIG.3.2.10. EXPERIMENTAL RESULTS OF VAPEX RUN 2.10



OIL PRODUCTION FOR RUN 910419

FIG.3.2.11. EXPERIMENTAL RESULTS OF VAPEX RUN 2.11



OIL PRODUCTION FOR RUN 910430

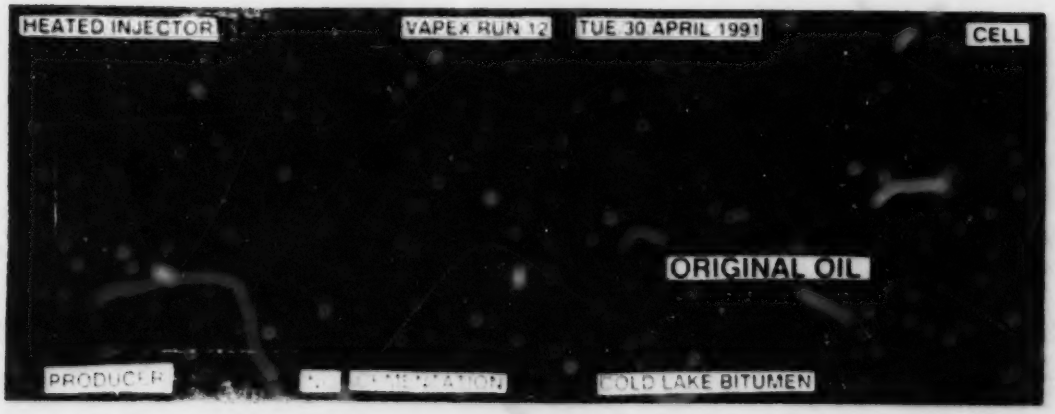
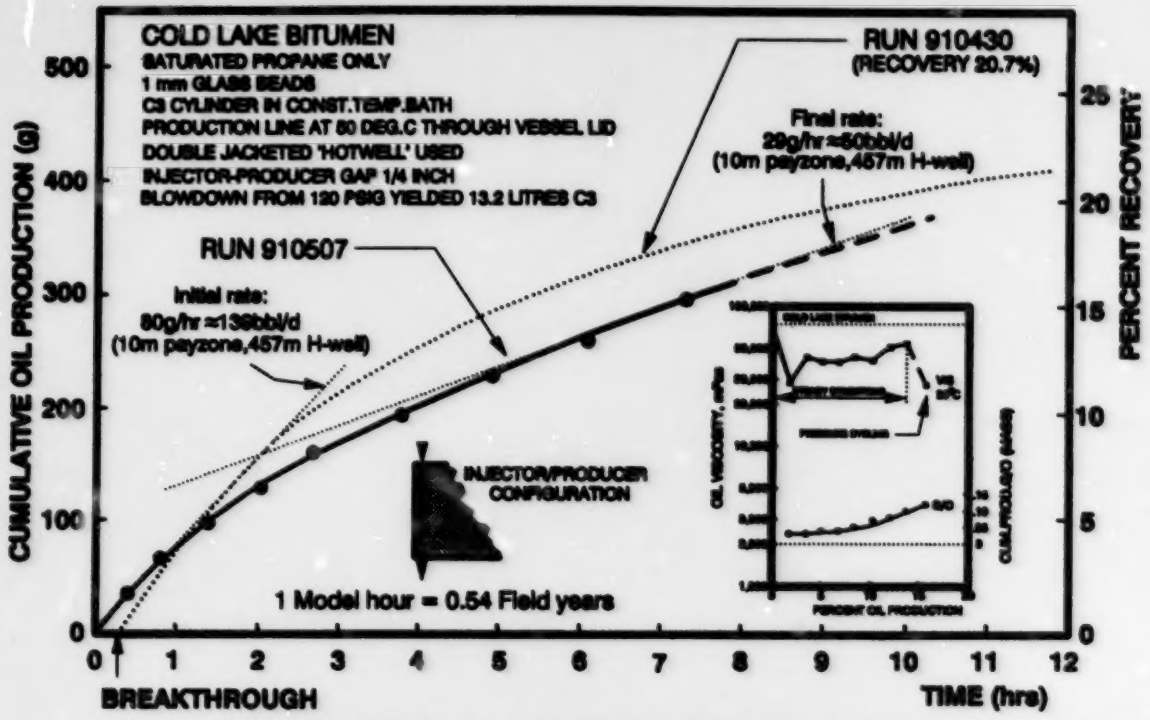


FIG.3.2.12. EXPERIMENTAL RESULTS OF VAPEX RUN 2.12



OIL PRODUCTION FOR RUN 910507

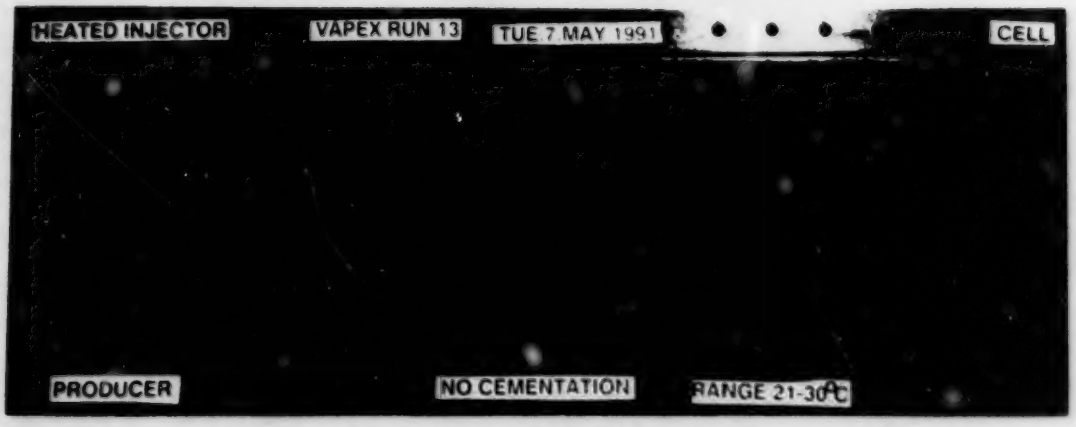
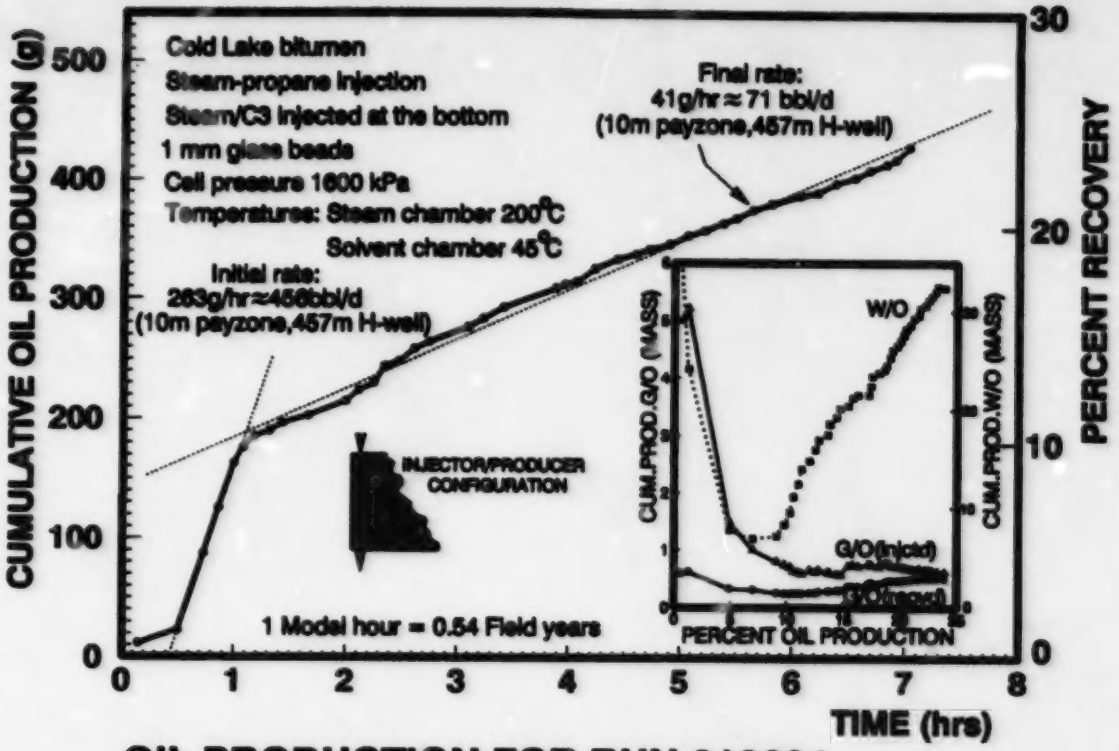


FIG.3.2.13. EXPERIMENTAL RESULTS OF VAPEX RUN 2.13



OIL PRODUCTION FOR RUN 910624

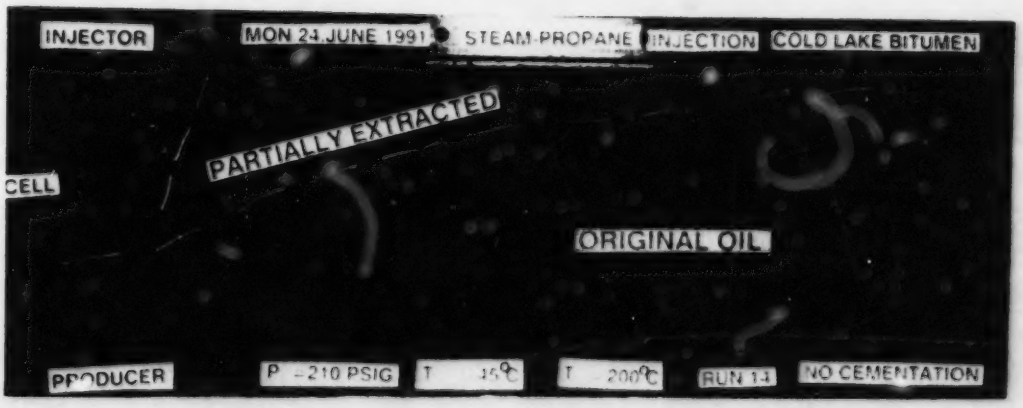
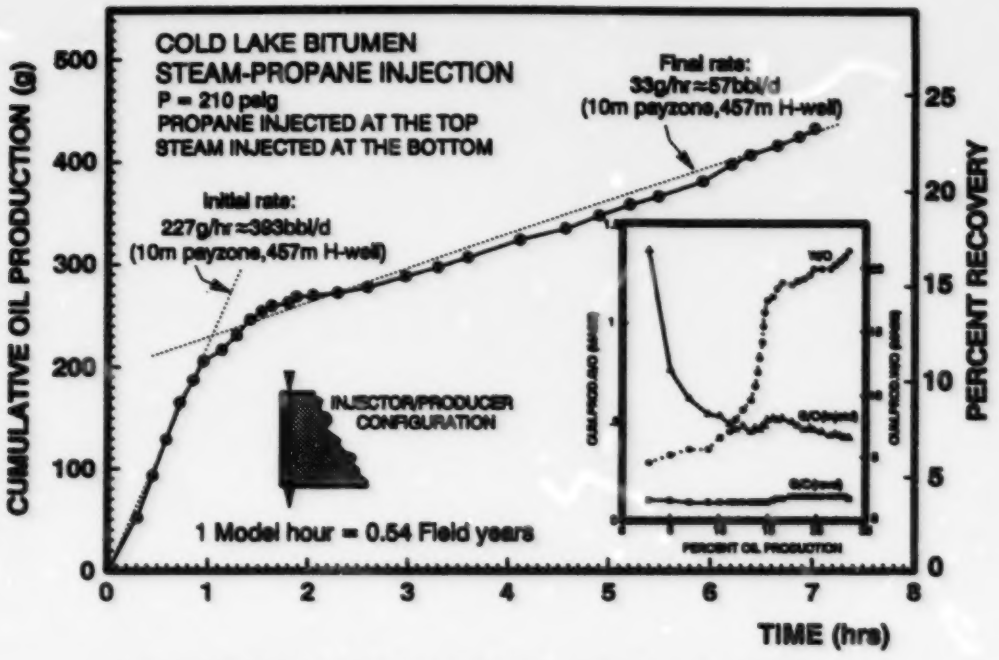
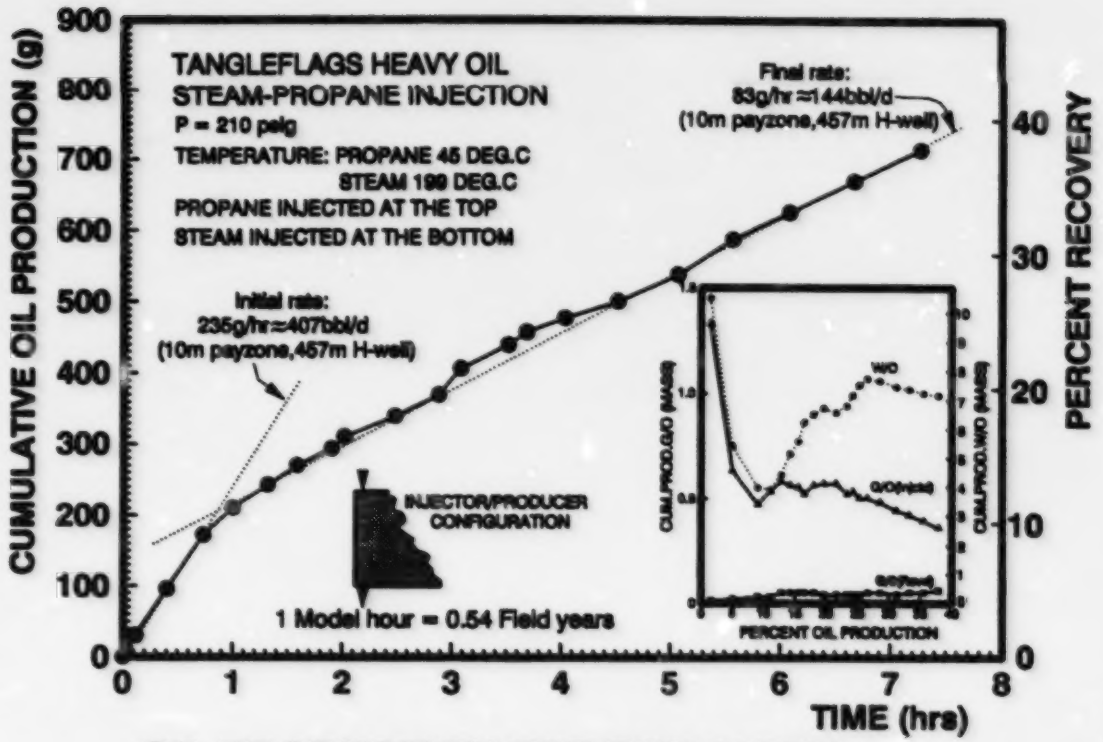


FIG.3.2.14. EXPERIMENTAL RESULTS OF VAPEX RUN 2.14



OIL PRODUCTION FOR RUN 910726

FIG.3.2.15. EXPERIMENTAL RESULTS OF VAPEX RUN 2.15



OIL PRODUCTION FOR RUN 910809

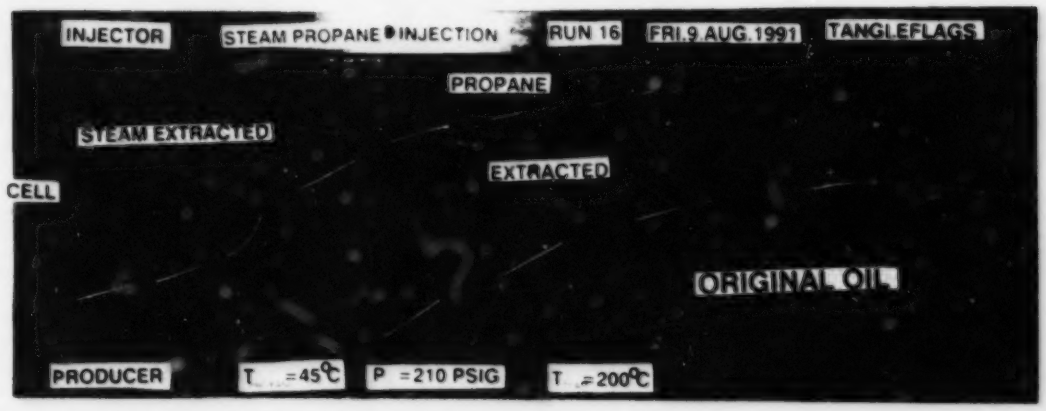


FIG.3.2.16. EXPERIMENTAL RESULTS OF VAPEX RUN 2.16

3.3 Phase 2 Experiments on Propane-Bitumen Mixing: Effect of Deasphalting on Dead Oil Viscosity.

Pentane Deasphalting

The initial objective of mixing heavy oil and bitumen with excess pentane (i.e., with a poor solvent) was to find the asphaltene content of the oil samples. It eventually developed into a study of the effect of propane deasphalting on the oil viscosity.

The deasphalting of Cold Lake bitumen and Tangleflags heavy oil with 50:1 to 80:1 excess n-pentane was carried out at room temperature. The procedure takes advantage of low solubility of heavy, high molecular weight asphaltene structures in low boiling saturated hydrocarbons. n-pentane is usually used as a standard solvent to precipitate out these complex materials from the oil. They are arbitrarily referred to as "asphaltenes" and the soluble part as "maltenes" [6].

Heavy oils are often compared on the basis of how many percent of these asphaltenes they contain. Asphaltenes obtained in this manner are complex mixtures of polycyclic aromatics or naphthenoaromatics with chains usually containing nitrogen, oxygen and sulphur, as well as trace metals such as nickel and vanadium. These metals are undesirable as they poison cracking catalysts.

The nature of asphaltenes depends on the conditions under which the precipitation took place and on the diluent. Asphaltenes precipitated by propane will be quite different in nature from those precipitated by pentane.

The pentane and oil were mixed thoroughly, the undissolved portion filtered off, dried for 3 days in the fume hood and weighed to calculate percent asphaltenes in the original crude. The filtrate was concentrated by distilling off some of the pentane in a rotary evaporator and then allowed to stand in a fume hood for a period of 5 days. The viscosity of the resulting lighter oil was then measured in a UKRV-8 rotary viscometer.

The time when pentane evaporation in the hood should be stopped, to prevent an increase in viscosity due to the loss of light fractions of the oil, was set at 5 days. This period was determined by comparing the viscosity of an evaporating sample of diluted bitumen (Fig. 3.3.1) over a period of days with that of an undiluted bitumen control sample exposed to the same conditions.

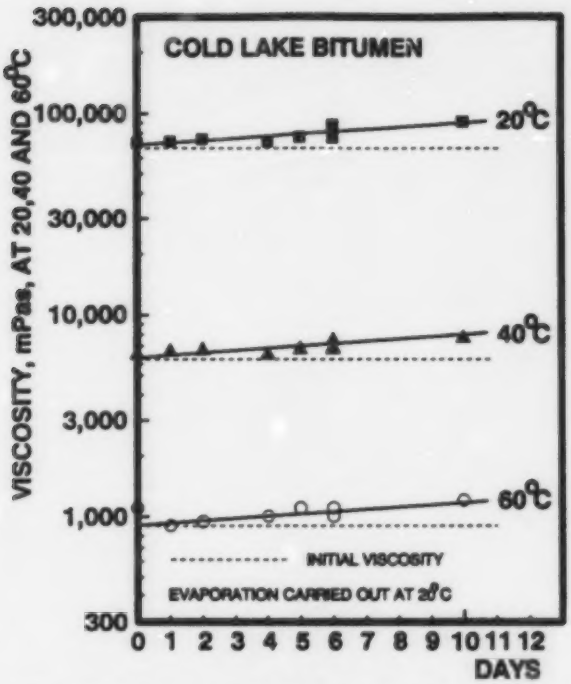


FIG.3.3.1. VISCOSITY CHANGES DUE TO EVAPORATION

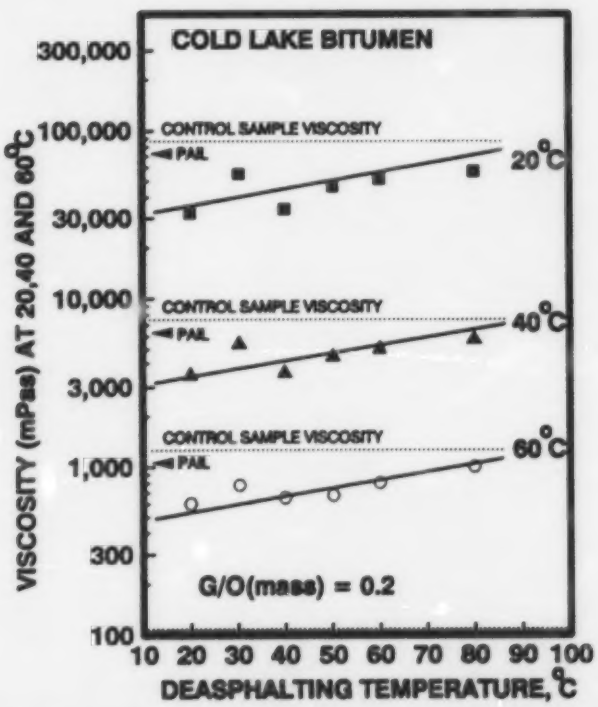


FIG.3.3.2. VISCOSITY OF PROPANE DEASPHALTED BITUMEN

Figure 3.3.2 was an exploratory experiment that illustrated the effect of temperature on the removal of asphaltenes from Cold Lake bitumen using propane, with a constant G/O ratio. The viscosity of the resulting oil was measured at three temperatures.

A pail sample viscosity of the original bitumen at 20, 40 and 60°C was also measured, as well as the viscosity of a pail sample that was allowed to evaporated in the fume hood for 5 days. This sample is called a control sample. The viscosity of the control sample increased slightly as a result of losses of low end boiling point components of the oil, however, this was compensated for in the deasphalted bitumen samples by the lowering of viscosity caused by the residue of dissolved propane gas. It is important to note that the pail sample viscosity of the original oil or bitumen varied from pail to pail.

The results show that the desphalting process is more effective at lower temperatures. Based on this conclusion, later propane deasphalting was carried out at a constant low temperature and with increasing amounts of gas.

Figures 3.3.3 and 3.3.4 show the effect of asphaltene content in bitumen or heavy oil on the viscosity of the resulting oil. The deasphalting was carried out with pentane at room temperature (20°C) and the viscosities were measured at 20, 40 and 60°C. The results show that Cold Lake bitumen contains initially 17.6% by weight of asphaltenes whereas Tangleflags heavy oil only 15.6%. The removal of asphaltenes by pentane lowers the Cold Lake bitumen viscosity from about 100,000 to about 4,000 mPas and the Tangleflags oil viscosity from about 10,000 to about 2,000 mPas. The quality of the resulting oil improves as the undesirable heavy asphaltenes are left behind, deposited on the glass beads.

Propane Deasphalting:

Further work was aimed at producing lighter oil using saturated propane vapour as a solvent. By virtue of being a poorer solvent for oil than pentane, propane, under the same conditions, removes more of the heavy components of bitumen and heavy oils, effectively upgrading them in situ.

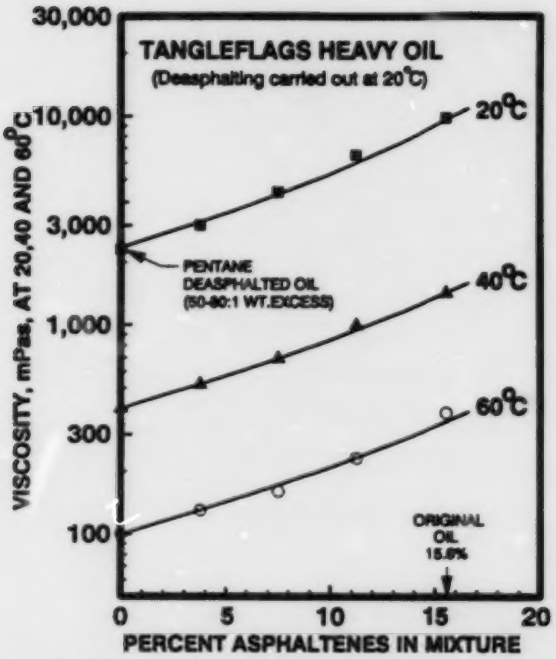


FIG.3.3.3. VISCOSITY OF PENTANE DEASPHALTED OIL Mixed with Various Proportions of Asphaltenes

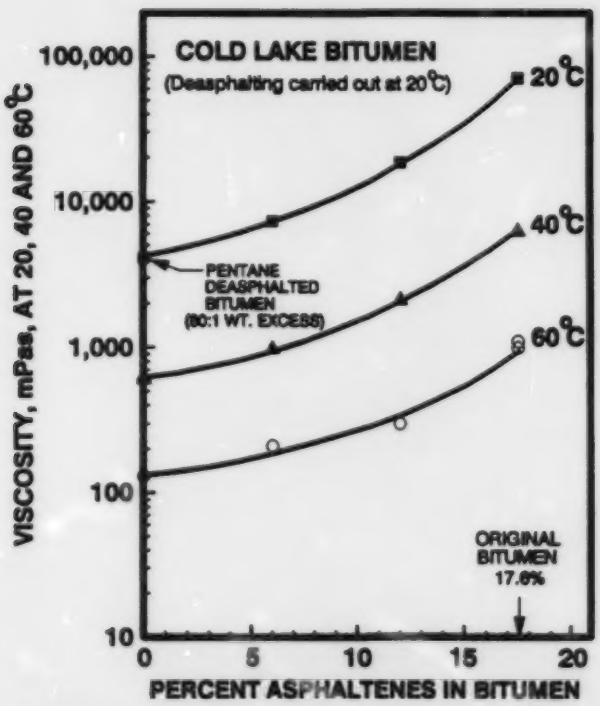


FIG.3.3.4. VISCOSITY OF PENTANE DEASPHALTED BITUMEN

To find out the extent to which this takes place, a series of experiments was initiated in which saturated propane vapour was mixed with the oil in a cylinder packed with glass beads (Fig. 3.3.5). The beads acted as a substrate with surface area available for the deposition of the heavy asphaltenes. This arrangement simulated the oil-propane contact in the scaled model (the cell) and provided results on deasphalting without actually performing a run in the cell. The advantages were simplicity and better control over experimental variables.

After being filled with the required mass of propane and oil, the cylinder was turned upside down at intervals of 15 minutes for four hours, oil drained and the gas allowed to escape from the oil over a period of 5 days before the oil viscosity was determined.

The results of a series of experiments with Cold Lake bitumen at 10, 20 and 80°C are plotted in Fig. 3.3.6. The gas-oil ratio (mass) increased from 0 to 1.5 (corresponding to 60% by weight of propane in the mixture) and the dead oil viscosity decreased from about 100,000 mFas to about 500 mPas if the mixing was carried out at 20°C, to about 1000 mPas if carried out at 10°C and to about 4000 mPas if the mixing temperature was 80°C.

The decrease in viscosity at 20°C is significant. If the high G/O ratio and other conditions can be reproduced in the cell (and later in a reservoir), an in situ upgraded product of higher quality can be produced directly from a horizontal well. However, further work remains to be done to study the potentially reduced permeability and its effect on the rate of production. Some of the answers could come from the experimental work of Phase 2 of this project and will be examined later.

The results in Fig. 3.3.6 have established a set of reference points for further work. The oil-propane contact in these experiments was probably better than that occurring at the oil-gas interface in the packed cell and the results therefore represent the upper limit of viscosity reduction by propane deasphalting for a given temperature and gas-to-oil ratio.

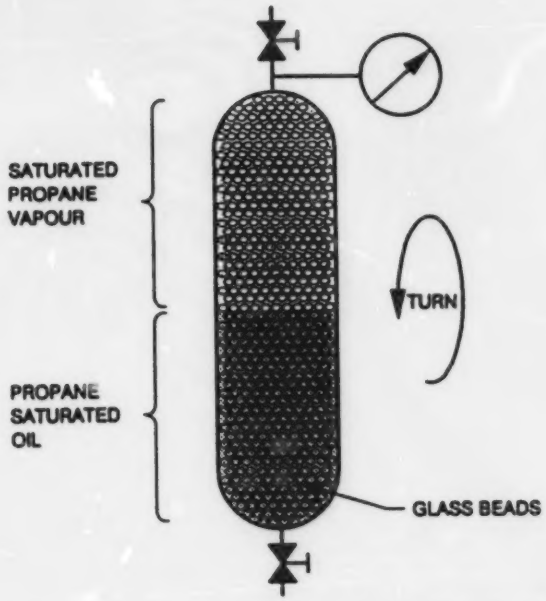


FIG. 3.5.5. APPARATUS FOR MIXING OF OIL WITH PROPANE

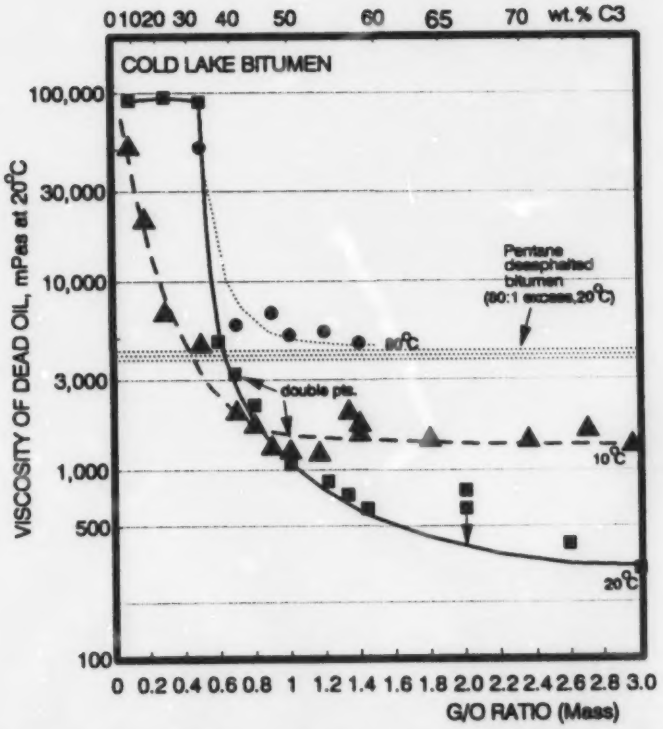


FIG.3.3.6. MIXING OF PROPANE WITH OIL: EFFECT OF G/O ON VISCOSITY

4. Adiabatic Mixing of Propane with Oil

Effect of Heat of Solution

Mixing of propane vapour with oil involves a phase change from gas to liquid. This phase transition is accompanied by a negative change of the enthalpy, i.e., heat evolves and is absorbed by the surrounding reservoir. The adiabatic rise in reservoir temperature depends on the amount of propane dissolved and on the heat capacity of the reservoir material. Higher heat capacity materials, such as water, absorb most of the heat. In our calculation we have assumed the following parameters for the reservoir: $S_o = 0.7$, $S_w = 0.3$ and the rock porosity $\phi = 0.35$. The average molecular mass of the oil was assumed 500 g/mol. The calculation shows that raising the temperature of 1 m^3 of reservoir by 1°C requires 2,146 kJ, or, to heat up that part of a reservoir containing 1 kg of oil by 1°C requires 8.9 kJ.

An approximate enthalpy-composition diagram for mixtures of a wet reservoir tar sand and propane is given in Figure 4.1. The abscissa of the diagram represents the composition of the binary oil-propane hydrocarbon mixture (propane does not dissolve in water to any extent), plotted as the weight fraction of oil. The right ordinate is the change of enthalpy of a reservoir per kg of oil above an arbitrary 20°C datum; the left ordinate is the change in enthalpy per kg of liquid propane (bottom) and per kg of propane vapour (top) above the 20°C datum line.

The isotherms sloping downwards to the left show the enthalpies of mixtures of liquid propane and reservoir materials for temperatures ranging from 20°C to 60°C. Liquid propane is assumed to mix with the reservoir oil with no heat of mixing and the isotherms are therefore straight lines.

The isotherms sloping down to the right represent the enthalpy of mixtures of propane vapour at 20, 40 and 60°C respectively, with the reservoir materials (in fact only the reservoir oil mixes) at 20°C. The heat of mixing is assumed to be the latent heat of condensation.

Superimposed on the same diagram is a set of curves representing the approximate weight fraction of oil in the oil-propane solutions in equilibrium with propane vapour at pressures ranging from 121 to 277 psia and temperatures from 20 to

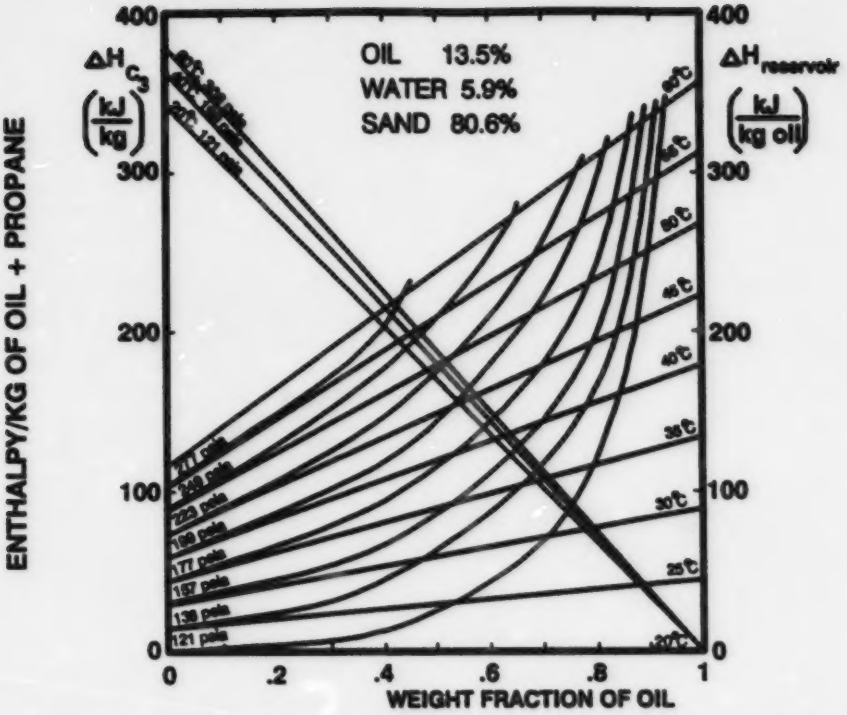
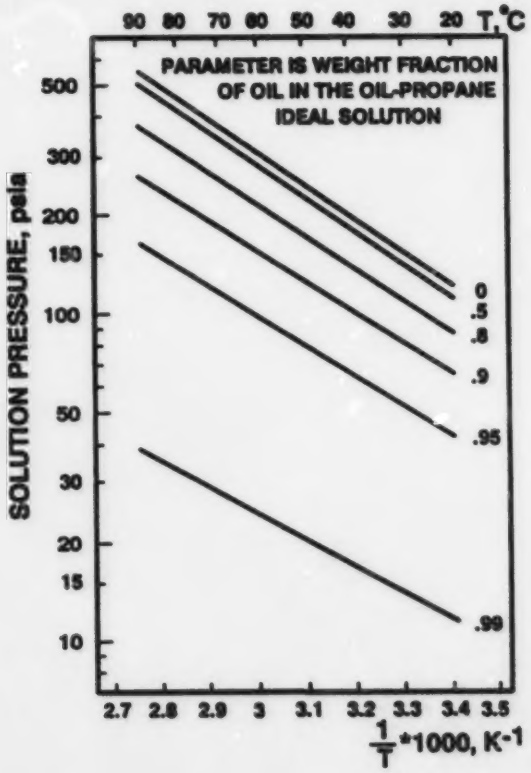


FIG.4.1. ENTHALPY OF PROPANE/OILSAND MIXTURE

FIG.4.2



60°C. These curves were constructed using approximate vapour-liquid equilibrium constants, predicted from reference [7].

This diagram can be used to predict the approximate composition of propane vapour-oil equilibrium mixture in the cell during an experiment and the effect of latent heat of solution of propane on the reservoir. If, for instance, the propane is injected into the cell at room temperature (20°C, 121 psia), the weight fraction of heavy oil in the binary hydrocarbon liquid mixture is about 0.75 and the temperature of the 20°C reservoir would be raised to about 32°C. These values are obtained from the intersection of the isotherm for 121 psia and the corresponding vapour-liquid equilibrium curve for 121 psia. The reservoir would be heated by about 12°C if a sufficient amount of propane vapour were injected to produce oil saturated at 121 psia; this oil would contain 25 wt.% propane (G/O = 0.33).

Cumulative gas-to-oil ratios of 0.5 are not uncommon in our experimental work (33 wt.% C_3) at higher propane pressures (132 psia). The predicted cell temperature under these conditions is about 35°C. For comparison, experimentally observed temperatures rose to 32-33°C.

Effect of Dissolved Oil on the Vapour Pressure of Propane-Oil Mixtures

Figure 4.2 illustrates the effect that a non-volatile oil has on the vapour pressure of a propane-oil solution. This figure is approximate and also makes use of the vapour-liquid equilibrium data utilized in Fig.4.1. The parameter is the weight fraction of oil in the mixture and the top line is therefore a plot of the Antoine equation for propane. As can be seen, an addition of non-volatile oil has a relatively small initial effect on the vapour pressure of the mixture. However, this effect becomes more pronounced at higher concentrations of oil.

Effect of Propane Addition on Asphaltene Precipitation and Solution Temperature

Increasing the amount of propane dissolved in oil raises the mixture temperature and also, eventually, causes the precipitation of asphaltenes from the oil-propane mixture. The effects are illustrated in Figure 4.3. Experiments indicate (see Fig. 3.3.6)

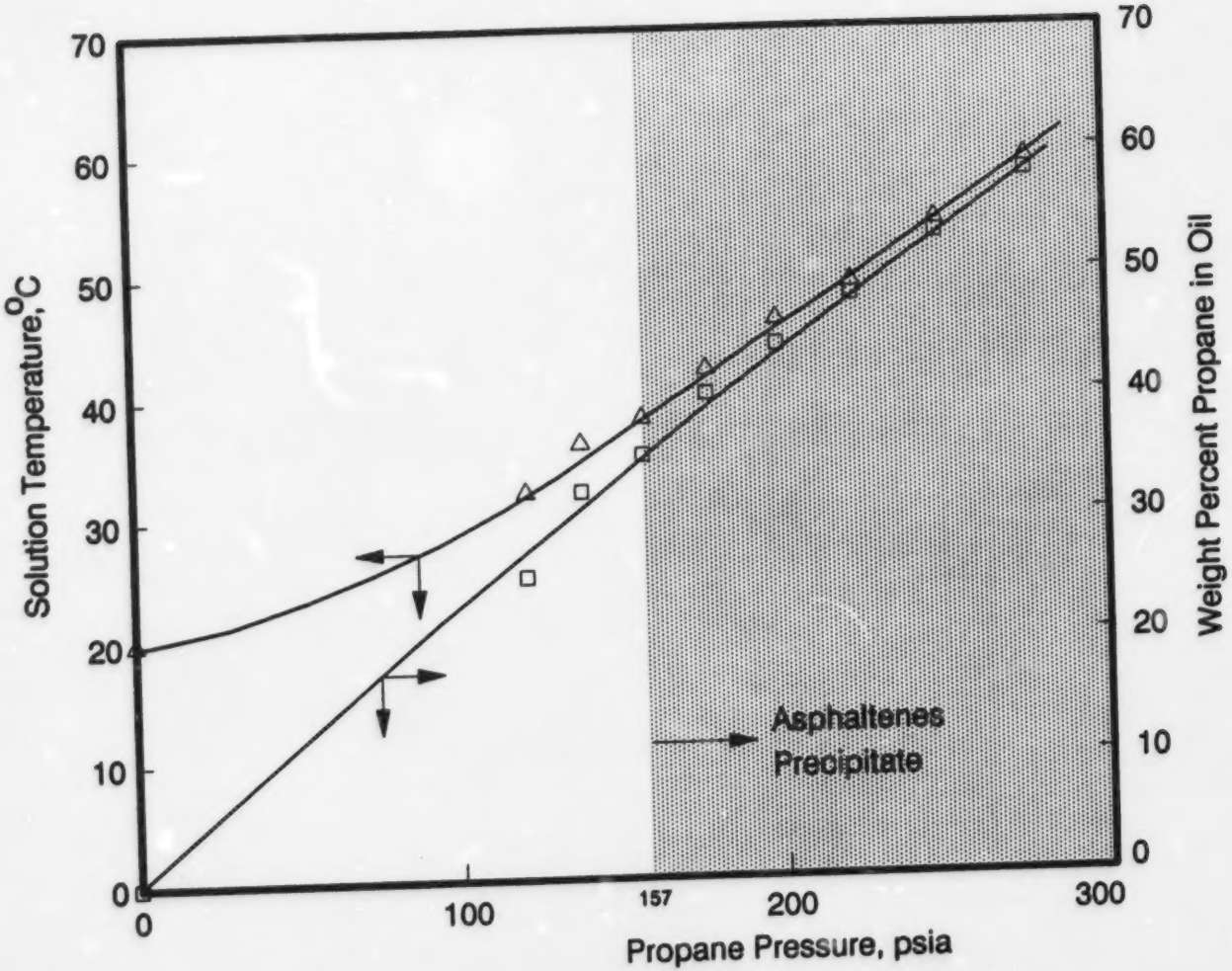


FIG.4.3. THERMODYNAMIC EXAMPLE:
EFFECT OF AMOUNT OF C3 ON TEMP.RISE AND ASPH.PRECIPITATION

that asphaltenes begin to precipitate out of the propane-Cold Lake bitumen solution in the region of 33 to 37 wt.% of propane (G/O = 0.5 to 0.6). Higher amounts of propane are required to effect further removal of asphaltenes (shaded area in Fig. 4.3). The figure suggests that, for an initial reservoir temperature of 20°C, the onset of asphaltene precipitation from adiabatic mixing with propane vapour would occur at about 157 psia in a reservoir such as that considered in the construction of Figures 4.1, 4.2 and 4.3. In the laboratory experiments, the onset was observed at about 133 - 135 psia with Lloydminster heavy oil. It is thought that the pressures for the development of a particular maximum propane concentration would be lower than those calculated above because:

a) the heat capacity per unit volume of the reservoir would be higher in the laboratory because of the mass of the thick walls of the model,

b) the dissolved propane is not uniformly distributed as is assumed in the above calculation.

Nevertheless, the observed effects approximate those which are expected from the theoretical consideration.

The upper curve in Fig. 4.3 indicates the temperature rise of the propane-oil mixture as a result of heat of solution of propane when a 20°C reservoir oil is mixed with propane vapour. For instance, increasing the propane pressure to 130 psia will result in an oil-propane mixture temperature of about 33°C, a number consistent with experimental observations. The curve also predicts an average temperature increase of 18°C/100 psi in the range of 100 to 300 psia.

5. DISCUSSION

Vapex Runs in the Scaled Packed Model

This part of the discussion refers to Figures 3.2.1 to 3.2.16.

Run 2.1 was carried out in a cell packed with (20-30 mesh) Ottawa sand. The cell permeability was approximately 120 darcies. Hot water at 90°C was injected for an initial period of 1.5 hours, resulting in a 22% recovery of oil. Propane vapour was then co-injected and, as a result, the oil recovery increased to 38% after 6 hours. The photograph of the opened cell (Fig.3.2.1) shows three main areas of interest: the vertical portion near the injector/producer in which oil was recovered by hot water; the laterally spreading vapour chamber in the top part of the cell in which the oil was recovered by saturated propane vapour; and the bottom section below the diagonal in which the sand remained at its original saturation. Of particular interest are the dark coloured streaks of deposited asphaltenes running parallel with the drainage paths of the oil. They are the testimony to the spontaneous in situ upgrading of the oil. The solvent chamber area was found to be consolidated in the vicinity of the streaks but no serious impairment of the drainage flow was observed. Recoveries were estimated without the use of Karl-Fischer analysis for water by dilution and centrifuging the samples with an emulsion breaker; this method is less accurate than that used in other experiments.

Run 2.2, as well as the following experiments, was carried out in the cell vibro-packed with 1 mm glass beads and the oil production was determined accurately using the Karl-Fischer analysis for water. The initial hot water flood was carried out to completion and propane injection commenced at 1 hour and 35 minutes. The cell pressure was maintained at 210 psig and the vapour chamber temperature at about 45°C. The injection well was located directly above the producer. The oil production increased from about 10% at the beginning of propane injection to 62% at the end. The initial scaled field rate of 867 bbl/d (for a 10 m reservoir) slowly declined to about 260 bbl/d after 6 hours of experimental time (26 yrs of field time). The W/O and G/O ratios reached a sharp peak at the end of the hot waterflood. At 50-60% cumulative oil production, the G/O ratio reached a value of 0.7-0.8 and the W/O was maintained at a steady value of 13 by the diaphragm metering pump. Both ratios refer to the recovered

gas and water, respectively. The initial increase in the G/O ratio is due to filling the cell and saturating the oil with propane. The effect of the propane on the recovery is seen to be dramatic.

The cell was opened at the end of the run and examined (Fig.3.2.2). The beads in the propane recovered area (marked cemented area in the photograph) were found to be consolidated by the deposited asphaltenes. The recovered oil was therefore of a better quality than the original oil.

Run 2.3 was carried out at 60°C and 280-290 psig during the propane phase. Initially, however, hot water was injected for 2 hours and it recovered about 15% of the OOIP. The oil production in the propane phase was initially 220 bbl/d and tapered off to about 45 bbl/d, reaching a recovery of 33% in 7 hours of experimental time. An examination of the open cell (Fig.3.2.3) revealed an oval cemented area right in the drainage path of the oil and this had an adverse effect on the recovery. The intended conditions of 60°C and 280-290 psig for the propane injection phase were not properly maintained throughout the whole of the run.

Run 2.4 was a repetition of the conditions used in run 2.3, i.e., 60°C and 280-290 psig for the propane vapour chamber. However, the temperature briefly reached 80°C, resulting in an irregular area of consolidated (cemented) beads (Fig.3.2.4) which impaired the drainage (accentuated by a white string in the photograph). The cumulative oil recovery was only 33% OOIP after 10.5 hours and the rate was diminishing in spite of attempts to stimulate production by cycling the pressure. The result is a wavy oil production curve between 6 and 10 hours of experimental time.

Run 2.5 suffers from the same deficiency, i.e., high operating pressure and temperature. The hot waterflood maintained the temperature locally at 75°C and, although the target conditions for the propane phase were 60°C and 280-290 psig, the temperature rose to 78-87°C shortly. The unstable conditions resulted in the cementing the beads with precipitated asphaltenes into a hard cake (see photograph in Fig.3.2.5) that impaired the drainage flow. This resulted in a high G/O ratio (1 or more) and low recovery (about 25%). The production rate between 5-8 hours was a steady, but low, 28 bbl/d. This was the last run with hot waterflooding.

Run 2.6 was performed with propane injected alone. The vapour chamber temperature was maintained at 30-35°C and the pressure at 150-180 psig. The recovery reached 33% after 6 hours and the rate averaged 97 bbl/d between 2-5 hours of experimental time. The opened cell showed some cementation, although the affected volume was not consolidated to a solid hard cake.

The viscosities of collected samples were measured and the results revealed a gradual decrease from 10,000 mPas initially to about 200-500 mPas at 30% recovery (see inset in Fig.3.2.6). This demonstrated the degree of in situ upgrading that can be achieved with Lloydminster oil and propane vapour during an experiment in a scaled, packed cell. Six samples were also taken from the cell and analyzed for residual oil. It was determined that the residual oil saturation in the extracted area was 0.29, in the cemented area, 0.78 and, in the partially extracted area, 0.70. However, it should be pointed out that the oil continues to migrate, after the experiment, within the pores under the forces imposed by gravity, and the result of S_{or} determination depends strongly on the way the sample is collected. The above mentioned data are plotted as insets in Fig. 3.2.6. The original oil saturation was close to 1.0.

Run 2.7 was carried out at conditions of 120 psig and 27-30°C for the vapour chamber. The recovery and the rate of recovery are somewhat similar to those of Run 2.6. Asphaltenes were deposited on the glass beads substrate, however, no solid layer of cemented beads was found when the cell was opened (Fig.3.2.7). The viscosity of the produced samples (see inset) diminished from 16,000 mPas to about 6,000 mPas and, inexplicably, then it increased and decreased again. The photo of the cell was taken the following day, by which time the area around the producer was re-flooded with draining oil and some backflush caused oil entry at the injector. These artifacts were absent immediately after the experiment was ended.

Run 2.8 was carried out at target conditions of 120 psig and 25-30°C with a new well configuration. The injector and producer were located on a diagonal (see Fig.3.2.8 inset) to improve the overall sweep efficiency. As a result of this staggered well configuration, the recovery rose to 53% in 8 hours and the recovery rate diminished from the initial 270 bbl/d to the final 126 bbl/d. The target conditions were maintained

steadily throught the duration of the experiment, corresponding to about 4.4 yrs of field time for a field of 10 m thickness.

A pair of 1500 ft horizontal wells drilled at the top and bottom of a 10 m payzone with 1 darcy permeability would be expected to produce, over this period, about 295 kB of an in situ upgraded Lloydminster type oil.

The quality of the produced oil was improved substantially, as indicated by the viscosity curve (inset of Fig.3.2.8). Also note on the photograph the streaks of deposited asphaltenes parallel to the drainage paths of the oil. The viscosity of the produced oil stabilized at a value of about 2000 mPas at 20°C, i.e., five times lower than the oil at the start of the experiment. This viscosity is higher than the 200-500 mPas in the Vapex Run 2.6, but is about the same as the viscosity of Tangleflags heavy oil that was deasphalted with 50 to 80:1 weight excess of pentane, as indicated by a dotted line in the graph for viscosity. The conditions for Run 2.6, i.e., 30-35°C and 150-180 psig, were therefore more conducive to an *en masse* asphaltene precipitation.

The major difference, and the main contributing factor to the removal of asphaltenes from oil, is the gas to oil ratio. Whereas the final value of the cumulative G/O=0.2 for Run 2.8, which results in a relatively modest drop in oil viscosity to 2000 mPas, the same ratio for Run 2.6 reaches a cumulative value of almost 1.5, resulting in oil viscosities as low as 200 mPas, (i.e., 50 times lower than at the start). The effect of G/O ratio on the produced oil viscosity was amply demonstrated in the work on propane-bitumen mixing and is described in Section 3.3 of this report.

Run 2.9 was the first of three runs intended to utilize saturated ethane vapour as a solvent. However, the cell pressure of 580 psig at 24-28°C turned out to be high enough to liquify most of the ethane. This showed as a presence of a transparent liquid in the high pressure cell with a sight glass (Fig.3.1.12). The run was therefore stopped after only 3 hours of experimental time. The viscosities of the produced oil samples were largely unaffected and the cumulative G/O ratio at 20% recovery reached a very low value of 0.03.

Run 2.10 entailed the injection of ethane vapour only into the unheated, insulated, packed cell, originally at 20°C. The ethane was preheated to 56°C in the heater coil of

the constant temperature tank, located immediately before the pressure vessel (Fig.3.1.3). The cell pressure was maintained at 545-550 psig and the vapour chamber temperature gradually rose and stabilized in the range of 27-32°C. The rise in cell temperature was due to both the sensible and latent heat of solution of ethane. The shortcoming of the run was that the ethane cylinder was maintained at a constant room temperature for the length of the experiment, i.e., at 21°C, and this arrangement therefore did not compensate for the increasing cell temperature. As a result, in the course of the experiment, the ethane vapour became more and more undersaturated.

The oil production reached 27% after 8 hours of experimental time and the final scaled field rate was 66 bbl/d. The dismantled cell showed no sign of bead consolidation. This was confirmed by viscosity measurements of the produced samples which indicated a constant value of viscosity (the slight apparent increase in viscosity (Fig.3.2.10 inset) may be due to an unintended removal of some light ends of the oil evaporation). The cumulative G/O ratio reached a low value of 0.16 after 8 hours of experiment.

In Run 2.11, an attempt was made to maintain the injection of saturated ethane into the scaled model. The ethane cylinder was immersed in a large water-filled container whose temperature (and therefore the ethane vapour pressure) was gradually increased to stay in step with the requirement for saturated vapour for the gradually warming solvent chamber within the packed cell. The cell pressure increased from 561 psig at the start to 595 psig at the end and the chamber temperature rose from 21°C to 27-28°C. Oil recovery reached 21% after 7.5 hours and the final scaled field rate was 42 bbl/d.

The cell was examined at the end of the experiment. It showed a laterally spread vapour chamber and no signs of consolidation. The viscosity of produced oil remained constant within experimental error (Fig.3.2.11 inset). Although saturated ethane drained the heavy oil from the cell, the rate was slow and the recovery low, compared to propane. Also, no in situ upgrading of the heavy oil occurred - at least none was observed in these experiments.

Run 2.12 utilized a pre-heated, double jacketed injector (see Fig.3.1.8) to facilitate a breakthrough in the cell filled with Cold Lake bitumen. The tip-to-tip distance

between the injector and the producer was approximately 0.25 inch and 70°C hot water was circulated through the double jacket of the injector until a breakthrough occurred. The run was accomplished by injecting propane at room temperature (21°C). The cell pressure was maintained at 110 psig and the temperature of the vapour chamber between 27-30°C. The propane in the cell was therefore undersaturated (cf. Fig.3.1.16). Bitumen recovery reached 20% after 11 hours with a final rate of 28 bbl/d. Bitumen viscosities remained virtually unchanged.

The cell was dismantled and examined the next day. The beads showed no sign of consolidation and a developing vapour chamber was apparent in the proximity of the injector. The white triangular area (Fig. 3.2.12) was not large enough to account for the 20-21% cumulative oil recovery so additional bitumen drainage must havwe been occurring along the drainage slope above the producer. The cumulative produced G/O ratio reached a relatively low value of 0.08 but a mass balance revealed that there were some leaks during the run and the actual G/O ratio was 0.12.

The apparatus for Run 2.13 is shown in Fig. 5.1. The propane cylinder was suspended on a beam attached to a load cell and immersed in a thermostated water bath. The load cell read out was displayed on the computer screen together with thermocouple temperatures. The cell temperature rose gradually from 21°C to the range of 30-36°C. No propane pre-heater was used and, since the pressure vessel lid acted as a large heat sink, 70°C hot water was circulated through a double jacket of the production line to maintain the produced bitumen in a liquid state. Further downstream, the production line was heated with an electric tape.

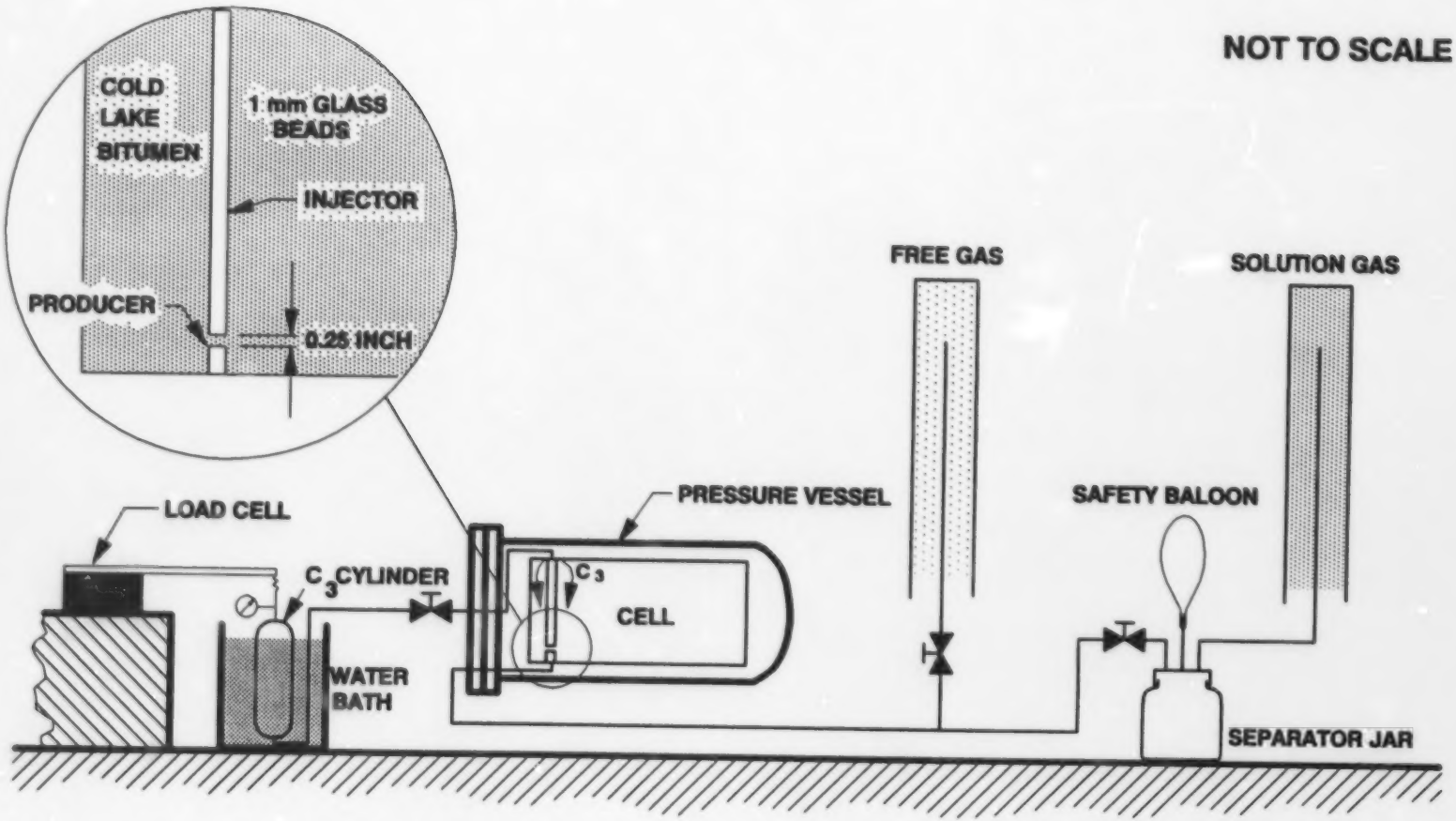


FIG.5.1. SATURATED PROPANE INJECTION FOR RUN 910507

Cell pressure was increased during the run from an initial 111 psig to the final 132 psig and, after 7 hours of experimental time, the pressure was cycled with the purpose of stimulating further production but without much success. The production reached 16% after 7.25 hours while the initial rate of 139 bbl/d declined to about 50 bbl/d. At that point, the run was stopped.

Dismantling the cell the next day revealed a patch of clean beads next to the initially heated injector. This however does not account for 16% production and additional drainage occurred in the vicinity of the injector/producer. The viscosity of the produced bitumen decreased from 100,000 to 40,000 mPas but no solid cementation of beads was observed. The cumulative gas to oil ratio reached a final value of 0.12 and a comparison between the production curves for Runs 2.12 and 2.13 is apparent from Fig.3.2.13.

An area of a potential problem with this injector/producer configuration was the closeness of the solid bottom of the injector to the producer (the propane was injected sideways at the top of the cell). The gap was only 6 mm and if any blockage or consolidation occurred in this narrow space, the gravity drainage would have been severely restricted. If indeed this was the case in the two runs (2.12 and 2.13) is not known.

In the last three runs (2.14-2.16), steam was injected simultaneously with propane. The target conditions are given below.

Table 5.1

	T_{Sat}	P_{Sat}
Propane	45°C	210 psig (assuming P_{bar}=12.75 psig)
Steam	199°C	210 psig

The objective was to test the coexistence of a steam chamber at the bottom of the cell with a propane vapour chamber at the top and their effectiveness in recovering Cold Lake bitumen, and later, Lloydminster-type oil. It is believed that the hot steam near

the production well strips propane from the draining diluted oil and this propane recycles into the vapour chamber. The propane vapour then condenses into a fresh surface of oil exposed by the draining solution of propane in oil. However, additional propane is required to maintain pressure and the G/O ratio as the chamber grows. The chambers thus create two distinct temperature zones - a hot 199°C bottom steam chamber and a relatively cool 45°C upper vapour chamber.

The Vapex concept of redirecting the hot propane vapour back to extract more oil has its analogy in a distillation column or a soxlet apparatus. It should be noted that the relative proportions of steam and propane can vary from pure steam injection to pure propane injection and any combination thereof. The hydrocarbon vapour can be actually viewed as a steam additive to recover economically upgraded heavy oil from thin formations.

A schematic of the apparatus for Run 2.14 is given in Fig.5.2 and a detail of the cell/thermocouple wires/pressure vessel flange in a photograph in Fig.3.1.2. The photograph also shows the steam-condensate knock-out pot with a thermocouple. The purpose of this addition was to separate condensed steam after its passage through the massive flange and to assure the injection of high quality steam into the cell. Since the standard laboratory steam supply was at too low a pressure, a separate, available steam generator was used.

During Run 2.14, both steam and propane were injected near the bottom of the cell. The cell temperature was maintained at 200-205°C but the cell pressure was off target at 230-240 psig. The produced oil was cooled to 90°C (Fig.5.2) and oil/water/emulsions collected in a jar. The solution and free propane were measured separately and compared with gas injected as recorded by the load cell and displayed on the screen.

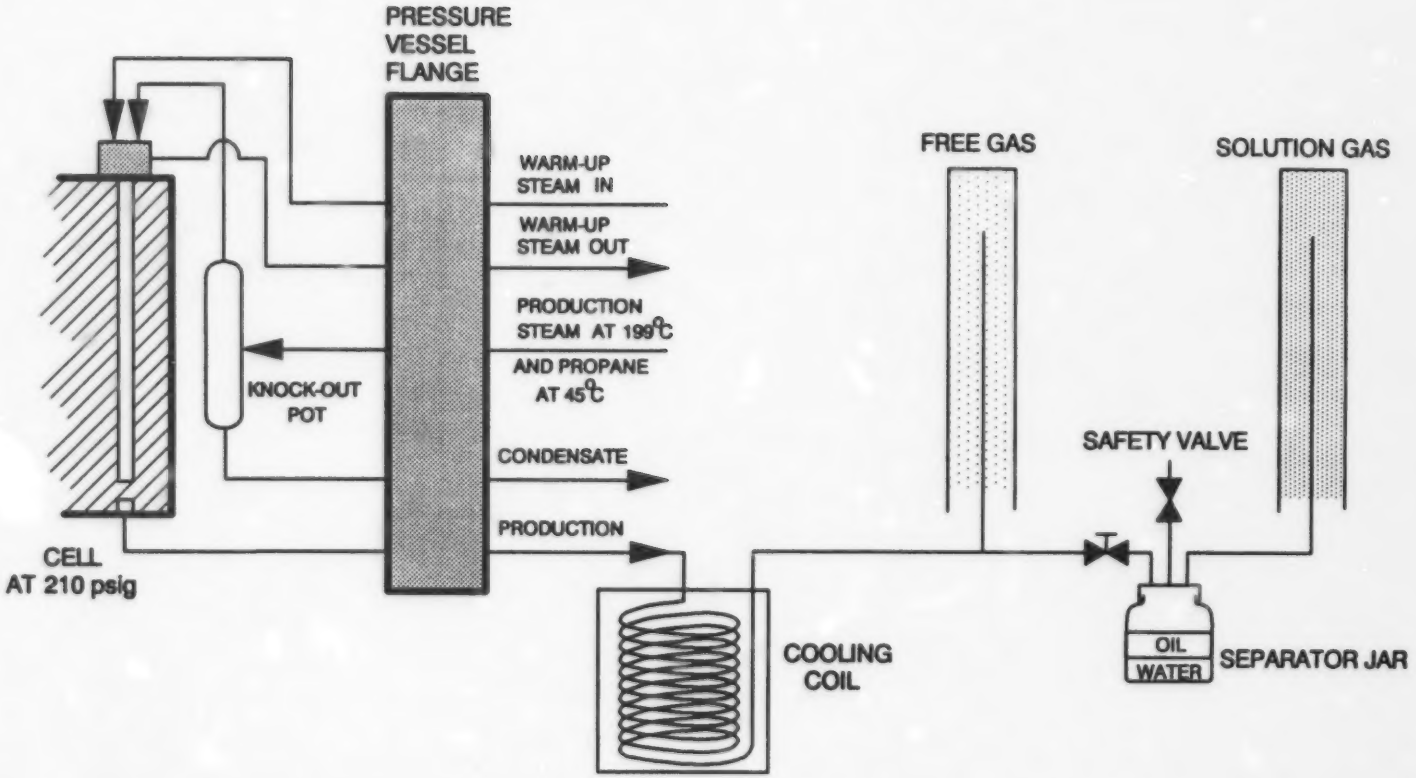


FIG.5.2. STEAM-PROPANE INJECTION APPARATUS

The recovery of Cold Lake bitumen reached 25% in 7 hours (Fig.3.2.14) at a final rate of 71 bbl/d. Both the injected and recovered gas to oil ratio reached a final value of about 0.55 while the W/O ratio reached 33. This high value is the result of steam passing directly, uncondensed, from the injector to the production well and then condensing in the product cooler. That this was happening was not realized until after the experiment. The high WOR is not significant. The amount of produced water was determined accurately by the Karl Fischer analysis of the oil/water/emulsion fractions collected in the course of the experiment.

A photograph of the dismantled cell (taken the following day) showed three distinct regions (Fig.3.2.14); the area of white beads near the injector is the former steam chamber (about 200°C) and was extracted by steam. The laterally spread lighter area was the solvent vapour chamber and was extracted by the saturated propane vapour (about 45°C). The dark sloping area contains unrecovered oil. Its curvature originally led to the producer but the space near the producer became filled with oil after the experiment was ended and before the photograph was taken.

The side-by-side existence of propane and steam chamber proves experimentally that once the propane chamber has been formed, it will not get invaded by steam. The heat will be transferred to the propane at the propane chamber boundary. The whiter beads in the steam chamber area testify to the fact that 200°C steam is a very effective means of bitumen extraction. The darker area of the vapour chamber is caused by some deposition of asphaltenes. This was confirmed by viscosity measurements on two oil samples listed below.

Table 5.2

Time	Viscosity (mPas at 20°C)
44 min.	31,600
60 min.	56,800

The Cold Lake bitumen viscosity was originally about 100,000 mPas.

The major change in Run 2.15 was the injection of propane at the top of the cell

(formation), while steam was injected near the bottom. The cell temperature near the producer was maintained at 200°C and the cell pressure at 210 psig. The recovery of Cold Lake bitumen reached about 24% after 8 hours. The scaled rate of production was almost constant between 1.5 and 7 hours at 57 bbl/d. The cumulative injected G/O ratio reached the value of 0.42, the lower recovered G/O ratio indicates that there was a leak in the apparatus.

The photograph in Fig.2.15 was, unfortunately, taken the following morning, and the white string indicates approximately the drainage slope. The lighter colour of beads near the injector was the steam chamber and the darker area on the side is the vapour chamber with some asphaltenes left behind.

The same experiment repeated with the Tangleflags heavy oil (Run 2.16) produced 38% of the OOIP in 7.3 hours at a rate of 144 bbl/d (Fig.3.2.16). This rate and recovery were not as good as in pure propane Run 2.8 in which the combination of experimental conditions was just right.

The dismantled cell shows the 3 characteristic regions and also an area, directly above the producer, that could be associated with drainage impairment. Considering the high steam temperature in combination with asphaltene precipitation, it seems likely that local consolidation occurs, just like it occurred in runs with hot water. That would then account for the relatively lower rates and recoveries. It is considered that the high WOR's found in Run 2.16 are caused by uncontrolled steam bypass and are not significant.

Further experiments with steam and propane are planned for the next phase of the project. These will use improved geometries and operating procedures and having a model of improved design.

6. CONCLUSIONS

1. Vapex may become an economically attractive recovery method for reservoirs in which high heat losses occur.
2. An inherent feature of a propane-oil contact can be the separation and deposition of heavy asphaltenes. The benefit of this process is the in situ upgrading of the original oil that results in a lighter oil of better quality that is more suitable for direct refining. This advantage may make the process attractive even in reservoirs where Steam-Assisted Gravity Drainage would also be economic.
3. Experiments have shown that during the oil-propane contact, the viscosity of Lloydminster-type oil can be lowered 5-50 times and that of Cold Lake bitumen, 100 times.
4. The main factor influencing the propane deasphalting is thought to be the gas to oil ratio in the oil at the perimeter of the chamber. Higher G/O ratios result in more deasphalting.
5. A careful choice of experimental conditions, particularly temperature, can avoid the formation of consolidated material that impairs the drainage flow.
6. Ethane appears less effective than propane as an agent in this vapour extraction process.
7. The inclusion of steam with propane seems to be more beneficial for bitumens than heavy oils. Under the right conditions, heavy oils can be recovered quite effectively by propane alone. However, with the introduction of steam as well as propane, it may be possible to recycle propane in situ and reduce or eliminate the need for surface propane cycling facilities.
8. Experiments and calculations have shown that the dissolution of propane in oil can raise the interface temperature typically by 10-20°C.
9. The laboratory results show that the Vapex process may have potential as a useful recovery method for heavy oils.
10. The objectives for the next phase of the Vapex development should be to further define the optimum geometry and operating conditions so that one or more pilot field tests can be proposed.

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APPENDIX 1

LOAD CELL AMPLIFIER CIRCUIT

by Mike Grigg 90/09/20
University of Calgary

Overview

The project involved connecting two load cells to a Taurus data acquisition system. One load cell would monitor the weight change of water, the other propane. The desired results are to be able to tare a large weight (approximately 34 lbs for propane, 8 lbs for water) and sense a 5/90 lbs (propane/water) change in weight by using the maximum resolution of the Taurus. The Taurus uses a 12 bit A/D (analog to digital) converter which gives a resolution of 4096 counts or 0.0012/0.22 lbs/count (propane/water). To make use of the full resolution of the Taurus, the output of the load cell amplifier must be bipolar (ie., -50mv to +50mv).

The Circuitry

The load cell amplifier circuit is divided into 6 different blocks. These blocks are an instrumentation amplifier, zero circuit, amplifier and filter circuit, secondary buffer and filter circuit, 10 volt reference supply and power supply.

Instrumentation Amplifier:

An instrumentation type of amplifier was picked because of its temperature stability and the fact that this type of configuration does not load the circuit under measurement.

Initially it was decided to use the -50mv to +50mv range of the Taurus. Therefore, the instrumentation amplifier was required to produce a 100mv change in output voltage for a change in load of 5/90 lbs (p/w). Since the load cell produces a 0 to 20 mv output when connected to a 10 volt reference supply with a 50/100 lb (p/w) range, an output of 0.4/0.2 mv/lb (p/w) is seen. As we are looking for a 5/90 lbs (p/w) change in load, the change in output of the load cell is 2/18 mv (p/w). Therefore, the

gain of the amplifier is set to 49/5.5 (p/w) to give the required output.

Zero Circuit:

The zero circuit consists of a 'difference' amplifier which subtracts the voltage produced by a voltage divider from the signal from the instrumentation amplifier. The voltage at the output of the voltage divider is controlled by a 10 turn potentiometer an provides sufficient voltage to tare the load to -50 mv.

Amplifier and Filter Circuit:

Due to the extreme amount of noise encountered at the output of the zero circuit, a low pass filter had to be incorporated in the circuit. For the filter to be able to operate effectively, and to reduce the amount of noise picked up in transmission to the Taurus, the input signal was amplified by 200, producing a -10 to +10 volt output (a valid range for the Taurus).

Secondary Buffer and Filter Circuit:

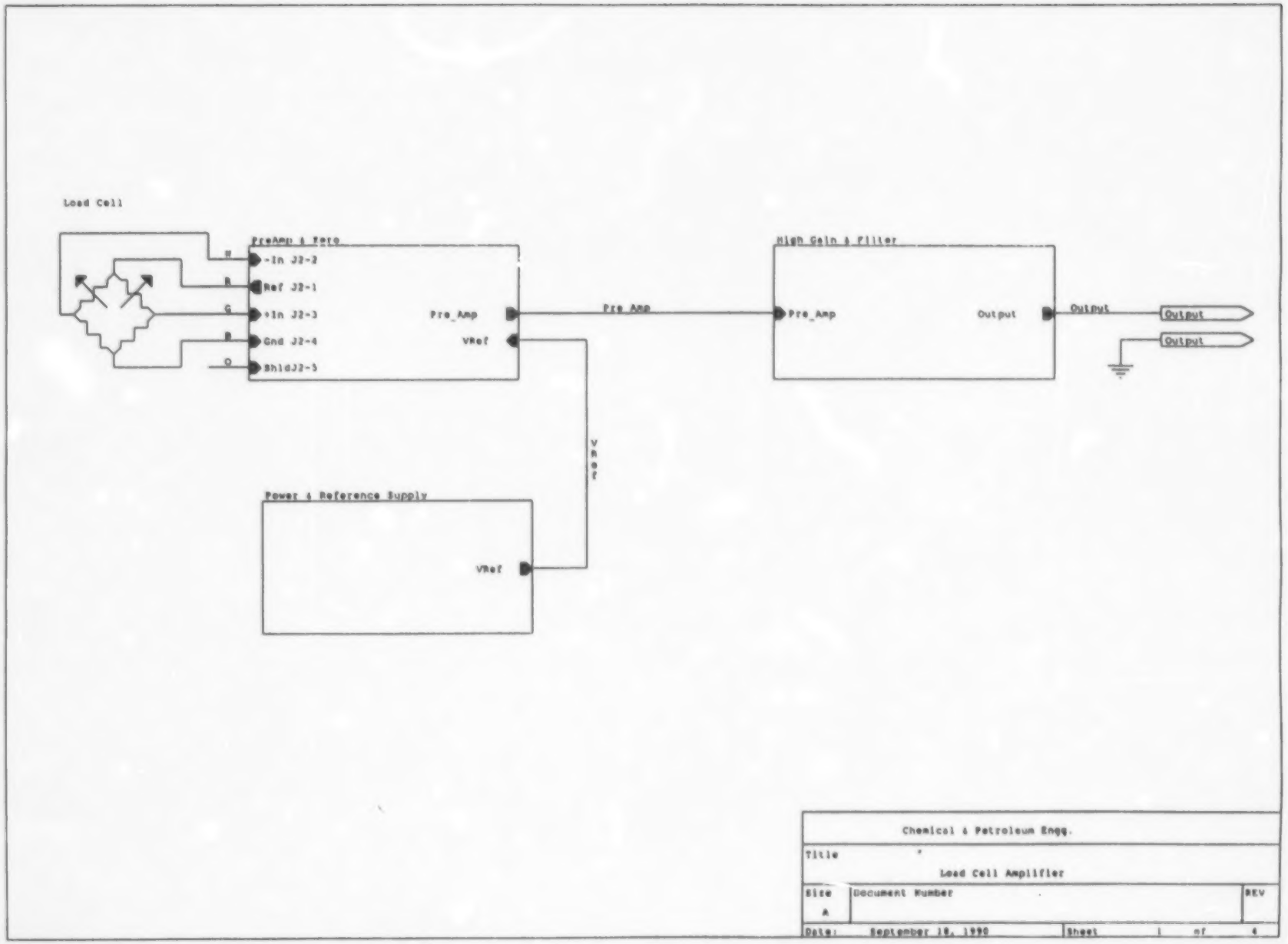
It was found that the filter circuit did not remove all of the noise in the input signal, so a second filter was added to the circuit. The second filter was buffered from the first by a unity gain amplifier to ensure that there were no adverse effects. This circuit is essentially a "band-aid", and the problem with the first filter circuit will be investigated at a later date.

Reference Power Supply:

The output of the precision 10 volt reference chip is not sufficient to drive the load cell, so a buffer amplifier and a driver transistor were added to the circuit. The buffer amplifier makes use of feedback circuitry to eliminate any losses occurred in the driver transistor.

Power Supply:

The power supply provides +15 and -15 volts to the op-amps and all other circuitry as required.


Load Cell
PreAmp & Pots
W
B
G
R
O
-In J2-2
Ref J2-1
+In J2-3
Gnd J2-4
ShldJ2-5
Pre_Amp
VRef
Pre Amp
High Gain & Filter
Pre_Amp
Output
Output
Output
Output
VRef
Power & Reference Supply
VRef
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Title
Load Cell Amplifier
Size
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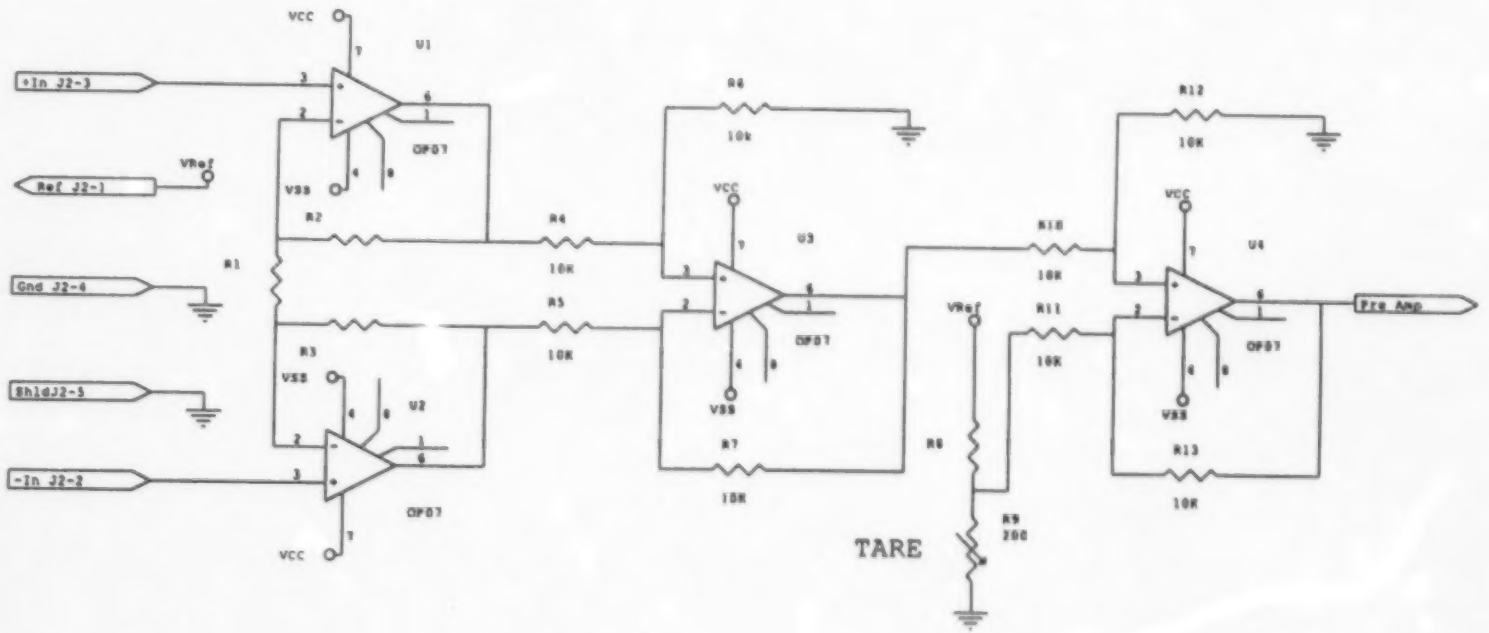
Date: September 18, 1990
Sheet 1 of 4



Meter Unit: R1=5230 R2,R3=10K R8=2510

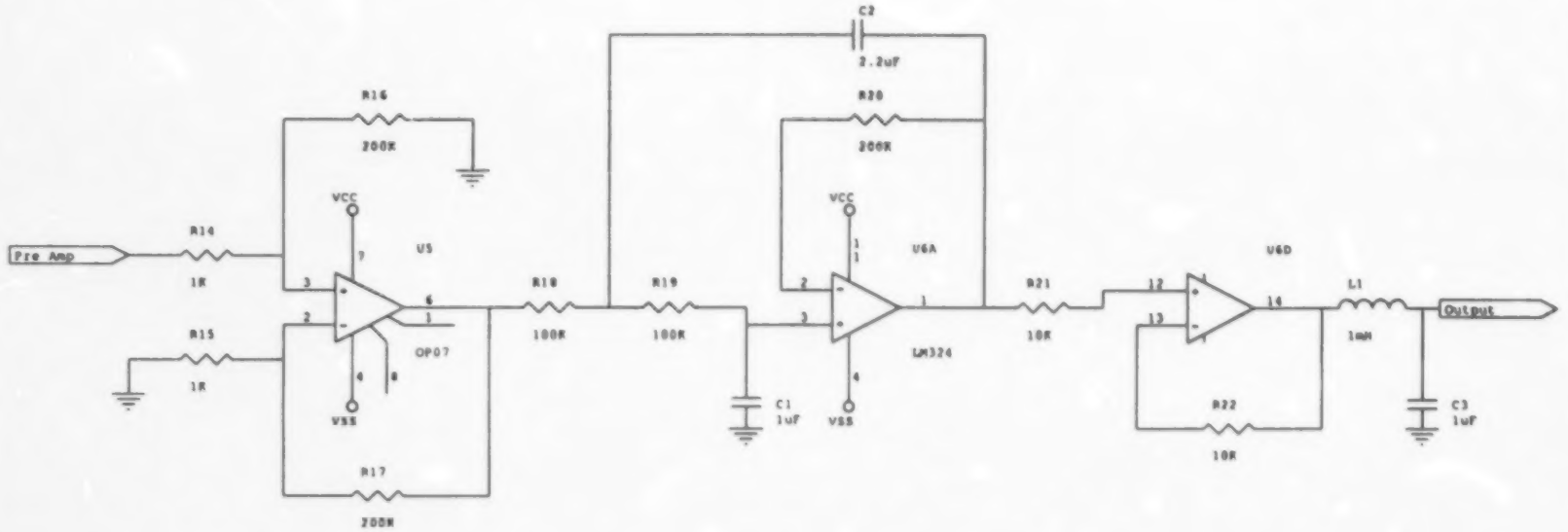
Propane Unit: R1=481 9 R2,R3=10K R8=1018

Original Unit: R1=400 R2,R3=20K R8=1050
Those values may be made up from one or more resistors

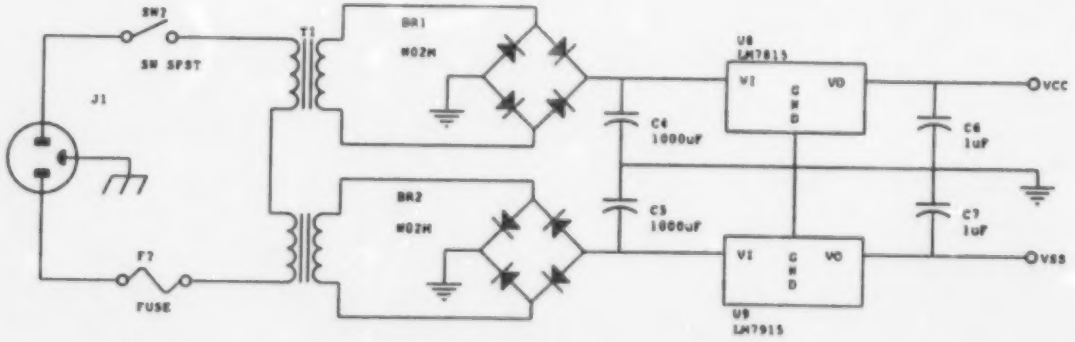
Note that all resistor values are in ohms

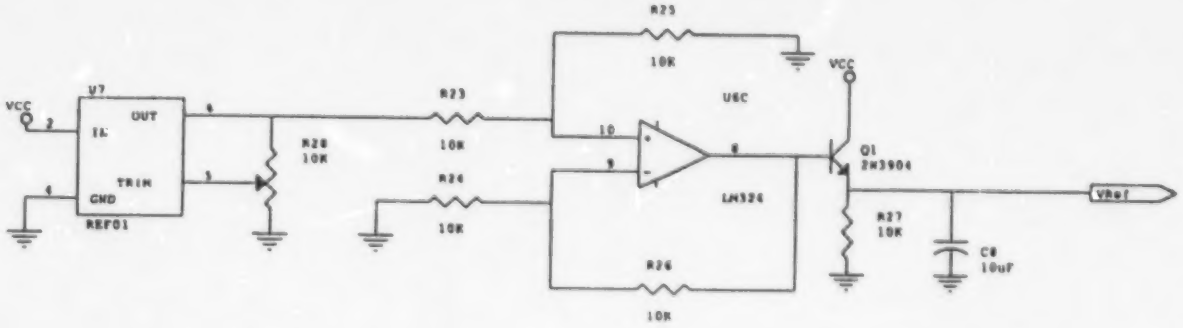
All resistors are metal film with 1% tolerance

Chemical & Petroleum Engg.		
Title: Load Cell Amplifier - Pre Amp & Zero		
Size: A	Document Number	REV
Date: September 18, 1990	Sheet 2 of 4	



Chemical & Petroleum Engg.		
Title: Load Cell Amplifier - High Gain & Filter		
Size: A	Document Number	REV
Date: September 19, 1990	Sheet 3 of 4	





Chemical & Petroleum Engg.		
Title: Load Cell Amplifier - Power & Reference Supp		
Size: A	Document Number	REV
Date: September 18, 1990	Sheet 4 of 4	

APPENDIX 2

Vapex Basic Program for Taurus Interface

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10 'PROGRAM FOR VAPEX EXPERIMENT, SUMMER 1990, U of C, D304
20 'PROGRAM MONITORS 61 THERMOCOUPLES AND 2 LOAD CELLS
25 TIME$="00:00:00" 'RESET TIME
30 PRINT CHR$(27)"1"CHR$(10)
40 DIM T(100),Z(100),TS(100)
50 CLS: WIDTH 80: LINE INPUT "IDENTITY OF EXPT (5 CHARACTERS, EG. RUN05)? ";NNN$
60 INPUT "ENTER TIME INTERVAL BETWEEN DATA RECORDING IN MINUTES";DELT$
70 LINE INPUT "DO YOU WANT TO STORE DATA ON A FILE ?  YES or NO = ";FF$
80 IF FF$="NO"OR FF$="N"OR FF$="n"OR FF$="no" OR FF$="No" THEN FF$="N":GOTO 160
90 LINE INPUT "WHAT IS THE NAME OF THE DATA FILE (8 CHARACTERS MAX.) ? ";FILE$
100 FILE$="A:"+FILE$
110 MJ=0 :'COUNTER IN DISK FILE RECORDS
120 OPEN FILE$ FOR OUTPUT AS #2
130 PRINT #2,NNN$+ "                    Temperatures in tenths of degrees C                "+DATE$:CLOSE #2
140 PRINT "THE NAME OF YOUR DATA FILE IS ";FILE$ 'ECHO PRINTING
150 REM------------------------------------------------------------------------
155 TIME$="00:00:00" 'RESET TIME
160 OPEN "COM2:9600,E,7,1" AS #1 'STAYS OPEN ALL THE TIME
170 TO=TIMER:IC=0:F=-1000:G=-1000 'INITIATE TO,IC,F AND G
180 PRINT #1, "$A0,1,IN"
190 INPUT #1, A$, B$
200 PRINT #1,"$A0,1,UC CA (18,10)" : 'RESET TAURUS ONE
210 INPUT #1,AA$,BB$,CC$
220 JJ=0 :'COUNTER USED FOR PRINTING
230 N1=29 :'29 TCs ON BUS #0
240 N2=31 :'32 TCs ON BUS #4
250 N=63 :'TOTAL NUMBER OF THERMOCOUPLES
260 A=60*VAL(DELT$):'A=SECONDS BETWEEN SCANNING THERMOCOUPLES
270 PO=2:WO=40 'INITIATE "OLD WEIGHTS" FOR PROPANE AND WATER
280 IF TIMER-TO>0 THEN TO=TO+A 'INCREASES To AT THE START ONLY
290 'BEGINNING OF READ/DISPLAY/WRITE SEQUENCE FOR LOAD CELLS
295 CLS:PRINT "Getting new data.  Please wait"
300 PRINT #1, "$A0,1,IN" 'INITIATE COMMUNICATION WITH BUFFER #1
310 INPUT #1,A$,B$ 'TAURUS' RESPONSE TO BUFFER #1
320 PRINT #1,"$A0,1,UC CA(18,18)" 'SET HANDSHAKE MODE
330 INPUT #1,AA$,BB$,CC$ 'TAURUS'RESPONSE
340 I=IC
350 PRINT #1,"$A0,1,RD AN(0,30)" 'READ C3 LOAD CELL ON BUS 0 AND CHANNEL 30
360 INPUT #1,D$,E$,F$ 'TAURUS' RESPONSE FOR PROPANE
370 PRINT #1,"$A0,1,RD AN(0,31)" 'READ H2O LOAD CELL ON BUS 0 AND CHANNEL 31
380 INPUT #1,DD$,EE$,G$ 'TAURUS' RESPONSE FOR WATER
390 I=I+1
400 FW=VAL(F$) 'PROPANE READING
410 'IF F<-999 THEN F=FW 'F=TAURUS VOLT READING FOR PROPANE CELL
420 'EXPONENTIAL FILTER
430 'IF ABS(F-FW)<50 THEN F=.9*F+.1*FW ELSE F=.99*F+.01*FW
440 GW=VAL(G$) 'WATER READING
450 'IF G<-999 THEN G=GW 'SET TO -1000 IN LINE 170
460 'EXPONENTIAL FILTER
470 'IF ABS(G-GW)<20 THEN G=.9*G+.1*GW ELSE G=.99*G+.01*GW
480 I=0
490 P=FW/200 'F=TAURUS VOLT READING FOR PROPANE LOAD CELL
500 P=P+.225 'ADJUST TAURUS READOUT TO -10.00V WHEN TARED
510 W=GW/200 'G=TAURUS VOLT READING FOR WATER LOAD CELL
520 W=W+.21 'ADJUST TAURUS READOUT TO -10.00V WHEN TARED
540 PN=P/9.197699+1.0872 'CALCULATE NEW WEIGHT OF PROPANE (kg)
550 WN=W/.5263+19.912 'CALCULATE NEW WEIGHT OF WATER (kg)
560 GOTO 570
580 RP=(PO-PN)/A*3600 'INSTANTANEOUS C3 RATE IN kg/hr
590 RW=(WO-WN)/A*3600 'INSTANTANEOUS WATER RATE IN kg/hr
600 PRINT "INITIAL WEIGHT OF C3 =";
610 PRINT USING "#####.###";PO;
620 PRINT " kg";
630 PRINT "          FINAL WEIGHT OF C3 =";
```

```
640 PRINT USING "#####.###";PN;
650 PRINT " kg"
660 PRINT "INITIAL WEIGHT OF WATER =";
670 PRINT USING "#####.##";WO;
680 PRINT " kg";
690 PRINT "       FINAL WEIGHT OF WATER =";
700 PRINT USING "#####.##";WN;
710 PRINT " kg"
720 PRINT "INSTANTANEOUS RATE OF PROPANE =";
730 PRINT USING "#####.##";RP;
740 PRINT " kg/hr"
750 PRINT "INSTANTANEOUS RATE OF WATER =";
760 PRINT USING "#####.##";RW;
770 PRINT " kg/hr"
775 IF FF$="N" THEN GOTO 815
780 OPEN FILE$ FOR APPEND AS #2 'WRITE DATA ON DISK FILE
790 PRINT #2,PO,PN,WO,WN,RP,RW
800 PRINT #2,"   "
810 CLOSE #2
815 PO=PN:WO=WN 'SAVE OLD WEIGHTS OF C3 AND WATER
820 'END OF READ/DISPLAY/WRITE SEQUENCE FOR LOAD CELLS
830 IF TIMER-T0>0 THEN T0=T0+A:SFLAG=1:GOTO 290
835 K$=INKEY$:IF (K$="s") OR (K$="S") THEN GOTO 290
840 GOTO 830 'WAIT UNTIL THE INTERVAL A ELAPSES
860 PRINT "     "
870 'START OF READ/DISPLAY/WRITE SEQUENCE FOR THERMOCOUPLES
880 FOR I=0 TO N1
890 N$=STR$(I)
900 PRINT #1,"$A0,1,RD TJ(0"+N$+")":'REQUEST DATA INPUT FROM BUS 0 FOR J-TYPE TC
910 INPUT #1,A2$,B2$,T(I)
920 'PRINT I,T(I)
930 NEXT I
940 FOR I=0 TO N1-2
950 Z(I)=T(I)/10!: TS(I)=T(I)
960 NEXT I
970 Z(59)=T(N1-1)/10!: TS(59)=T(N1-1)
980 Z(60)=T(N1)/10!: TS(60)=T(N1)
990 FOR I=0 TO N2
1000 N$=STR$(I)
1010 PRINT #1,"$A0,1,RD TJ(4"+N$+")":'REQUEST DATA INPUT FROM BUS4 FOR J-TYPE TC
1020 INPUT#1,A2$,B2$,T(I)
1030 NEXT I
1040 FOR I=0 TO N2-1
1050 Z(I+28)=T(I)/10!: TS(I+28)=T(I)
1060 NEXT I
1070 Z(61)=T(N2)/10!: TS(61)=T(N2)
1080 CLS
1090 T$=TIME$
1100 PRINT "TIME =  ";T$;:PRINT "        ";:PRINT DATE$
1120 PRINT CHR$(124);:PRINT "--------------------------------------------------------------------------------";:PRINT CHR$(
1130 PRINT USING "    ###";Z(3);:PRINT USING "      ###";Z(10);:PRINT USING "       ###";Z(17);:PRINT USING "      ###"
1140 PRINT USING "        ###";Z(38);:PRINT USING "     ###";Z(45);:PRINT USING "      ###";Z(52)
1150 PRINT USING "###";Z(0);:PRINT USING "      ###";Z(51);:PRINT USING "       ###";Z(14);:PRINT USING "      ###";Z(2
1160 PRINT USING "      ###";Z(42);:PRINT USING"               ###";Z(56)
1170 PRINT "  "
1180 PRINT USING "         ###";Z(7);:PRINT USING "          ###";Z(18);:PRINT USING "          ###";Z(28);:PRINT USIN
1190 PRINT USING "         ###";Z(49)
1200 PRINT USING "    ###";Z(4);:PRINT USING "      ###";Z(11);:PRINT USING "               ###";Z(25);:PRINT USING "
1210 PRINT USING "               ###";Z(46);:PRINT USING "      ###";Z(53)
1220 PRINT USING "###";Z(1);:PRINT USING "               ###";Z(15);:PRINT USING "      ###";Z(22);:PRINT USING "
1230 PRINT "    "
1240 PRINT USING "                     ###";Z(19);:PRINT USING "                        ###";Z(40)
1250 PRINT USING "         ###";Z(8);:PRINT USING "                          ###";Z(29);:PRINT USING "
1260 PRINT USING "    ###";Z(5);:PRINT USING "      ###";Z(12);:PRINT USING "               ###";Z(26);:PRINT USING "
```

```
1270 PRINT USING "                ###";Z(47);:PRINT USING "      ###";Z(54)
1280 PRINT USING "###";Z(2);:PRINT USING "                ###";Z(16);:PRINT USING "      ###";Z(23);:PRINT USING "
1290 PRINT USING "                      ###";Z(20);:PRINT USING "                              ###";Z(41)
1300 PRINT USING "         ###";Z(9);:PRINT USING "                                  ###";Z(30)
1310 PRINT USING "    ###";Z(6);:PRINT USING "      ###";Z(13);:PRINT USING "                              ###";Z(27);:PRINT USING "
1330 PRINT USING "                    ###";Z(60);:PRINT USING "      ###";Z(61)
1335 PRINT USING "###";Z(48);:PRINT USING "   ###";Z(59)
1340 PRINT CHR$(124);:PRINT "--------------------------------------------------------------------------------";:PRINT CHR$(
1360 IF FF$="N" THEN GOTO 580
1365 IF SFLAG<>1 THEN GOTO 580
1370 NJ=NJ+1 'ADVANCE COUNTER IN DISC FILE RECORD
1380 OPEN FILE$ FOR APPEND AS #2 'WRITE TC READINGS ON DISC FILE
1390 PRINT #2,"SCAN NUMBER"+STR$(NJ),"                TIME = "+T$
1400 FOR I=0 TO 61
1410 PRINT #2,T$(I);
1420 NEXT I
1430 PRINT #2,"   "
1440 CLOSE #2
1450 'END OF READ/DISPLAY/WRITE SEQUENCE FOR THERMOCOUPLES
1460 SFLAG=0
1470 GOTO 580
```